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On Electric and Magnetic Units and Dimensions

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THE subject of electric and magnetic units and dimensions is extensive and involved, and I have no desire to enter it in any detailed way. I should, however, like to summarize the fundamental ideas and equations, in order to clear up, as well as possible, certain misconceptions that were very common in the past and still persist in some texts at the present time. These misconceptions all seem to have arisen primarily as a result of the assumption that each sort of quantity possesses certain "natural" or "absolute" dimensions. Such a doctrine is held, for instance, by Starling[1] in a textbook that has gone through many editions. As a student, I had this idea of the matter, and have found it so difficult to outgrow such notions that as late as 1929 I stated[2] that the dimensions of dielectric constant ϵ and permeability μ were "unknown." For this I was very properly rebuked by Bond[3] in an article from which it appears that many distinguished scientists have in the past been found on each side of the question. This fact alone may afford an excuse for one further attempt to clear up a much debated matter.

The best book on the subject matter of dimensions is undoubtedly P. W. Bridgman's *Dimensional Analysis.* It is a book that should be read and digested by every teacher of physics. The fundamental thesis of this volume is that the dimensions of physical quantities are arbitrary or conventional rather than unknown. Moreover one cannot, from the adopted dimensions of a quantity, draw any final conclusion as to its physical nature; thus two quantities of quite different character, such as moment of force and energy, have, on the c.g.s. system, the same dimensions. If further support for Bridgman's views is desired, one can find it in Planck's excellent and authoritative text,[4] in which on p. 19 he states,

> "The fact that when a definite physical quantity is measured in two different systems of units it has not only different numerical values, but also different dimensions has often been interpreted as an inconsistency that demands explanation, and has given rise to the question of the 'real' dimensions of a physical quantity. After the above discussion it is clear that this question has no more sense than inquiring into the 'real' name of an object."

The plan of this paper is to summarize briefly the correct facts, as I now understand them, with occasional reference to a source where a similar point of view is maintained. Finally, in conclusion, I give a few examples of the actual misstatement of fact that can be found in the literature. In this connection it seems necessary to state that most texts fail not in what is actually said, but in what is *not* said. In a subject in which misconceptions can so easily arise, the most precise and explicit language is certainly demanded. The writer's experience has been,

[1] S. G. Starling, *Electricity and Magnetism,* 1st ed., 1912, 5th ed., 1929.
[2] R. T. Birge, Rev. Mod. Phys. **1**, 1 (1929). See p. 66.
[3] W. N. Bond, Phil. Mag. **9**, 842 (1930).
[4] Max Planck, *Theory of Electricity and Magnetism,* Eng. tr. by Brose, 1932.

however, that a great many texts seem to strive to avoid "commitments" on this particular matter, which is hardly a proper scientific attitude.

One can approach the question of the dimensions and numerical magnitudes of ϵ and μ in several different ways, as can be seen by a perusal of the various authoritative texts now available. The following approach seems to me the simplest to use in teaching the subject.

We find, from electrostatic phenomena, the relation

$$F = qq'/\epsilon r^2 \tag{1}$$

giving the force between two charges in a dielectric of dielectric constant ϵ. If the charges are in a vacuum we write

$$F_0 = qq'/\epsilon_0 r^2. \tag{2}$$

Hence

$$F_0/F = \epsilon/\epsilon_0 = \kappa, \tag{3}$$

where κ is the ratio of two forces, and is accordingly a pure number; that is, without dimensions and with the same numerical value, regardless of the system of units employed. We designate κ the *specific inductive capacity* of the medium, and distinguish it sharply from ϵ, the *dielectric constant* of the same medium. Such a distinction is rarely made in the literature,[5] for reasons to be given in a moment. From our point of view κ and ϵ are related just as are specific gravity and density; the first is necessarily dimensionless and of constant numerical magnitude, whereas the magnitude, and possibly the dimensions, of the second will depend on the system of units employed.

Now in Eq. (1) or Eq. (2) there are two *new* kinds of quantities, ϵ and q, not found in the simple mechanical phenomena. Accordingly the dimensions and numerical magnitude of *either ϵ or q* may be chosen *arbitrarily*. Then Eq. (1) *defines* the dimensions and magnitude of the other. In the ordinary electrostatic (e.s.) system of units we *assume* that ϵ_0 is *unity* and *dimensionless*. Then Eq. (2) *defines* the unit electrostatic charge, with the dimensions[6] of *length·(force)*$^{\frac{1}{2}}$; that is, $M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-1}$. Moreover, it follows from Eq. (3) that, *in the electrostatic system*, ϵ and κ are identical in magnitude and dimensions. Hence there is no possible distinction between the dielectric constant ϵ and the specific inductive capacity κ, and we may use the same letter for both. But such a statement is *not* necessarily true in any other system of units.

Having thus arbitrarily evaluated ϵ in Eq. (1), we are ready to introduce a new quantity D, the *electric induction*, or *displacement*. Its most general definition is

$$D = E + 4\pi P, \tag{4}$$

where D, E and P are vectors.[7] E is the *electric field intensity*, and P is the *polarization*, measured by the electric moment per unit volume. In the case of an isotropic dielectric, the displacement D is proportional to E and in the same direction; this gives the more specialized definition

$$D = \epsilon E. \tag{5}$$

Eqs. (4) and (5) are often combined as though they were equivalent, but this is not in general true (e.g., in a non-isotropic medium).[8] We see from Eq. (4) that D, E and P are all of the same dimensions, since every term of any equation necessarily has the same dimensions. Then from Eq. (5) ϵ is without dimensions, in agreement with our original assumption. But again we note that Eqs. (4) and (5) are written in e.s.u., and any deductions regarding dimensions drawn from them do not necessarily hold in any other system of units.

[5] The distinction is, however, made in the *International Critical Tables*. See **1**, 21, 36 and 41.

[6] On the other hand, in *any* system, the dimensions of electric charge are $M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-1}\epsilon^{\frac{1}{2}}$, where the dimensions of ϵ vary from system to system. This last expression is the one seen usually in the literature.

[7] The definition of D in Eq. (4) corresponds to 4π lines of induction drawn from each unit free charge. Several recent texts, such as those quoted in footnotes 8 and 16, use this definition. On the other hand, it was standard practise, a generation ago, to draw one line of induction per unit charge, giving the definition $D = E/4\pi + P$. This latter definition was used by Abraham and Föppl in their famous text *Theorie der Elektrizität*, which for many years held its place as the authoritative source of information on this subject. The same definition appears in J. J. Thomson's *Elements of Electricity and Magnetism* (3rd ed., 1904), probably in its day the most widely used book in English for courses of intermediate grade. Starling[1] has also used this definition in all editions. These two definitions of D illustrate the sort of variations that affects the magnitude but not the dimensions of a unit. We are, however, primarily interested only in those systems of units that lead to different *dimensions* of the quantities concerned.

[8] See, for instance, M. Abraham, *Classical Theory of Electricity and Magnetism*, Eng. tr. of 8th Ger. ed. by Dougall, 1932, p. 75. This text gives, on pp. 247–251, a very convenient set of formulas in the subject.

We now treat magnetostatics in a strictly parallel fashion. The force between two magnetic free poles is

$$F = mm'/\mu r^2, \tag{6}$$

where μ, the *permeability*, depends on the medium. In vacuum we have

$$F_0 = mm'/\mu_0 r^2. \tag{7}$$

Hence

$$F_0/F = \mu/\mu_0 = \kappa'. \tag{8}$$

This quantity κ' is so rarely introduced that it does not even have a name. It might be called *magnetic specific inductive capacity*. Like κ it is necessarily a pure number, with zero dimensions and with the same numerical value in all systems. Now in Eqs. (6) and (7), just as in Eqs. (1) and (2), we have two new quantities m and μ, one of which may be arbitrarily assigned dimensions and magnitude. In the ordinary electromagnetic (e.m.) system we *assume* that μ_0 is *unity* and *dimensionless*. Then Eq. (7) *defines* unit pole, on the electromagnetic system, with dimensions $M^{\frac{1}{2}}L^{\frac{3}{2}}T^{-1}$, precisely the same as those of unit charge on the electrostatic system. Furthermore, from Eq. (8), μ and κ' are, *in the electromagnetic system*, identical in magnitude and dimensions, so that one needs only the single symbol μ, called *permeability*, to denote both of them. Again, however, this identity does not necessarily hold in other systems.

Having thus arbitrarily evaluated μ in Eq. (6), we now introduce a new quantity B, the *magnetic induction*, whose most general definition is

$$B = H + 4\pi I, \tag{9}$$

where B, H and I are vectors.[9] H is the *magnetic field intensity*, and I is the *intensity of magnetization*, measured by the magnetic moment per unit volume. For isotropic para- or diamagnetic substances B is proportional to H, giving the special definition

$$B = \mu H. \tag{10}$$

[9] It is standard practise, as here, to draw 4π lines of magnetic induction from each free pole, and the chief advantage of the system used in Eq. (4) is that it best preserves the analogy between electrostatics and magnetostatics. As already noted, it seems to be coming into general use at the present time.

From Eq. (9) B, H and I have the same dimensions; hence, from Eq. (10), μ has zero dimensions in the e.m. system, but not necessarily in other systems.

We now proceed to obtain a general formula which yields the interrelations of the e.s. and e.m. systems, as well as other systems. To do this we write the well-known Maxwell equations

$$\operatorname{div} D = 4\pi\rho, \tag{11}$$

$$\operatorname{div} B = 0, \tag{12}$$

$$\operatorname{curl} H = (1/k)(4\pi i + \partial D/\partial t), \tag{13}$$

$$\operatorname{curl} E = -(1/k)(\partial B/\partial t). \tag{14}$$

The new quantities in these equations are ρ, the *density of free electric charge*, i, the *current density*, and k. It is this last quantity that is of special interest to us. At the present stage it can be considered as a constant introduced to make the two sides of Eqs. (13) and (14) balance dimensionally and numerically. Naturally its magnitude and dimensions will then depend on the units in which the other quantities in these equations are expressed. In the systems of units considered in this paper, the same constant k appears in both Eqs. (13) and (14), as written, but we shall not enter into the details of this matter.

In a homogeneous isotropic dielectric $i=0$, $\rho=0$, $D=\epsilon E$, and $B=\mu H$. Hence Eqs. (11) to (14) become

$$\operatorname{div} E = 0, \tag{15}$$

$$\operatorname{div} H = 0, \tag{16}$$

$$\operatorname{curl} H = (\epsilon/k)(\partial E/\partial t), \tag{17}$$

$$\operatorname{curl} E = -(\mu/k)(\partial H/\partial t). \tag{18}$$

These equations, as is well known, can be combined to give the partial differential equation

$$\nabla^2 W = (\epsilon\mu/k^2)(\partial^2 W/\partial t^2), \tag{19}$$

in which W is any component of E or of H. By comparing Eq. (19) with the famous equation of wave motion,

$$\nabla^2 W = (1/v^2)(\partial^2 W/\partial t^2), \tag{20}$$

one sees that Eq. (19) represents a wave with wave velocity

$$v = k/(\epsilon\mu)^{\frac{1}{2}}. \tag{21}$$

This is the fundamental equation, for the purposes of this paper. It is the most compact expression for the *necessary* numerical and dimensional relations between k, ϵ and μ.[10] It predicts the existence of electromagnetic waves of velocity v, and as has been shown experimentally, such waves do exist and have in vacuum the velocity of light, $v=c\sim3\times10^{10}$ cm/sec. Hence, for vacuum, Eq. (21) becomes

$$c=k/(\epsilon_0\mu_0)^{\frac{1}{2}}. \qquad (22)$$

Let us now consider this expression. It gives *one* relation—and the *only* known relation—between the *three* quantities k, ϵ_0 and μ_0. Hence we are at liberty to choose *arbitrarily* the magnitudes *and* dimensions of any *two* of these three quantities.[11] There are obviously an infinite number of ways in which such a choice can be made, and to *each* choice there corresponds a complete system of electric and magnetic units and dimensions. But among these innumerable possible choices, the *simplest* would appear to be those that assume two of the three quantities to have *unit* magnitude and *zero* dimensions. There are just *three* such possible choices, applied respectively to k and ϵ_0, k and μ_0, and ϵ_0 and μ_0. These three choices, in order, *define* the *electrostatic* system, the *electromagnetic* system, and the *Gaussian* system. These three systems alone are discussed in this paper. Of the remaining ones in actual use, each agrees with one or the other of these three in the *dimensions* of ϵ, μ and k, although one could evidently propose systems for which this would not be the case.

Having decided upon the dimensions and magnitudes of two of the three arbitrary quantities in Eq. (22), the dimensions and magnitude of the third are determined by the equation itself. We thus get Table I.

TABLE I.

System	Dimensions ϵ_0	μ_0	k	Magnitude ϵ_0	μ_0	k
e.s.	0	$L^{-2}T^2$	0	1	c^{-2}	1
e.m.	$L^{-2}T^2$	0	0	c^{-2}	1	1
Gaussian	0	0	LT^{-1}	1	1	c

[10] The dimensions of v are LT^{-1}; hence the necessary dimensions of $k/(\epsilon\mu)^{\frac{1}{2}}$ are LT^{-1}.

[11] Planck (reference 4, p. 15), speaking of this says "of these three constants two can, and, in fact, *must* be arbitrarily fixed. . . ."

The e.s. and e.m. systems have already been discussed, and a few remarks regarding the Gaussian system may be helpful. This is the system employed exclusively in most theoretical treatises on electricity and magnetism and, as we shall show, either intentionally or unintentionally, in most elementary textbooks also. In fact, one scarcely ever sees the Maxwell equations written in any other system. In the Gaussian system the k of Eqs. (13) and (14), or (17) and (18), is replaced by c, and this almost universal use of c, where I have written k, tends to create the impression that this constant is c ($\sim3\times10^{10}$ cm/sec.) in all systems of units—an impression that can easily lead to hopeless confusion in this subject.

In the Gaussian system, electric quantities are measured in e.s. units, and magnetic quantities are measured in e.m. units. This is the usual statement of the matter[12] but the phraseology seems to the writer rather misleading. It would be much more accurate to say "the units of electric quantities in the Gaussian system are identical in dimensions and magnitude with those of the e.s. system, and the units of magnetic quantities are identical with those of the e.m. system."

In this sharp division of all quantities into the two classes, electric and magnetic, there are certain possible ambiguities. Thus current and current density can be considered equally well as electric or as magnetic quantities. In the Gaussian system they are, however, commonly taken as electric quantities, so that the Gaussian units of these two quantities are identical with the e.s. units. This is true for Eq. (13), if k is replaced by c.[13]

A commonly employed system of units is the Heaviside-Lorentz (H.L.) system. All quantities in this system have the same dimensions as those

[12] See, for instance, *Smithsonian Physical Tables*, p. XLIV, and V. C. Poor, *Electricity and Magnetism*, 1931, p. 96.

[13] Thus Abraham (reference 8, p. 153) writes curl $H=(1/c)(4\pi i+\partial D/\partial t)$, corresponding exactly to our Eq. (13); that is, he considers current density as an electric quantity, and this is standard practise. But Jeans' *Mathematical Theory of Electricity and Magnetism*, p. 511, adopts, in our nomenclature, the form curl $H=(4\pi/c)(ci+\partial D/\partial t)$, which corresponds to current density considered as a magnetic quantity, and also to one line of induction per unit charge. All writers, including Jeans, consider electric charge as an electric quantity, so that, as used by Jeans, current is given not by the rate of passage of charge, $I=dq/dt$, but by $I=(1/c)(dq/dt)$.

in the Gaussian, so that the H.L. system is commonly classified as one form of the Gaussian system. The object of the H.L. system is to eliminate the factor 4π occurring in certain fundamental equations, so as to give the equations a more symmetrical form.[14] This question of the symmetry of the fundamental equations has been discussed fully and clearly in a recent article by Page,[15] but this is a subject on which I do not feel competent to pass judgment. It is also unnecessary to give a detailed tabulation of the relations between the various electric and magnetic units, as measured in various systems, since such a tabulation is given in many texts.[16]

Certain equations are, however, commonly written in only one system, so that it seems desirable to call attention to their form, as expressed in some other system. Thus relations between electric quantities are written almost exclusively in e.s. units, whereas relations between magnetic quantities are written exclusively in e.m. units. This practise indicates a certain misconception as regards the system of units employed. Thus if a writer regularly writes electric equations in e.s. units, and magnetic equations in e.m. units, he is employing *neither* the e.s. *nor* the e.m. system; he is, in fact, employing just the Gaussian system! I therefore agree emphatically with Abraham,[17] when he states that the e.s. system is rarely used, and that when the e.s. system is referred to, what is meant is the electric side of the Gaussian system.[18] Similarly when writers speak of the e.m. system, they usually have reference merely to the magnetic side of the Gaussian system. Occasionally, however, a writer does use the complete e.m. system. Thus Gilbert[19] discusses the Maxwell equations in terms of e.m. units exclusively. This text will be referred to again later.

In writing *all* quantities in the e.s. system, or in the e.m. system, it is necessary to use distinguishing subscripts. We shall use, as does Page,[15, 16] the subscript s for the numerical magnitude of any quantity as measured in e.s. units, and the subscript m for its numerical magnitude, as measured in e.m. units.

Thus Eq. (4) should be written

$$D_s = E_s + 4\pi P_s \tag{4'}$$

whereas, in e.m. units, it is written[20]

$$D_m = E_m/c^2 + 4\pi P_m; \tag{4''}$$

Eq. (5) is similarly written

$$D_s = \epsilon_s E_s \tag{5'}$$

or

$$D_m = \epsilon_m E_m \tag{5''}$$

where, from Table I,

$$\epsilon_m = \epsilon_s/c^2; \tag{23}$$

the magnetic Eq. (9) is written more precisely as

$$B_m = H_m + 4\pi I_m \tag{9'}$$

or as

$$B_s = H_s/c^2 + 4\pi I_s; \tag{9''}$$

and Eq. (10) is written

$$B_m = \mu_m H_m \tag{10'}$$

or

$$B_s = \mu_s H_s \tag{10''}$$

where, from Table I,

$$\mu_s = \mu_m/c^2. \tag{24}$$

As just noted, the relations between D_s and D_m, or B_m and B_s, etc., are commonly given in texts. The relations between ϵ_s and ϵ_m, and between μ_s and μ_m, as given in Table I and in Eqs. (23) and (24), are, however, usually not given, although these latter relations are basic to an understanding of the relationship of the various systems of units.

Table I may well be supplemented by a similar formulation for the index of refraction n, since this is a quantity concerning which misstatements are not uncommon. The index of refraction of a medium is defined as the ratio of the velocity of electromagnetic waves in vacuum to their velocity in the medium. Hence the most general formula for this quantity is that given by Eqs.

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[14] The H.L. system accomplishes this by the introduction of a new unit of charge, defined by $F = qq'/4\pi\epsilon r^2$, and a new unit of magnetic pole, defined by $F = mm'/4\pi\mu r^2$. From these new definitions there results $D = E + P$, $D = \epsilon E$, $B = H + I$, $B = \mu H$, $\mathrm{div}\, D = \rho$, $\mathrm{curl}\, H = (1/c)(i + (\partial D/\partial t))$, $\mathrm{curl}\, E = -(1/c)(\partial B/\partial t)$.

[15] L. Page, *Electromagnetic Equations and Systems of Units*, Physics **2**, 289 (1932).

[16] See, for instance, L. Page and N. I. Adams, *Principles of Electricity*, 1931, p. XII.

[17] See reference 8, p. 156.

[18] I have noticed the complete e.s. system in only one text, namely N. R. Campbell's *Modern Electrical Theory*, 2nd ed., 1913. Other nomenclature in this text is, however, unusual. Thus Campbell uses the term electric displacement and the symbol D for our $E/4\pi$, so that his D is actually only another unit of electric field intensity. He has no symbol or name for our D.

[19] N. E. Gilbert, *Electricity and Magnetism*, 1932.

[20] See reference 16, pp. 439–440 and reference 15, pp. 290–291.

(21) and (22), namely

$$n=c/v=(\epsilon\mu)^{\frac{1}{2}}/(\epsilon_0\mu_0)^{\frac{1}{2}}. \tag{25}$$

It is, however, customary to substitute in this equation the numerical value of ϵ_0 and of μ_0, holding for the system of units used. The resulting formulas can also be obtained conveniently from another general formula for n, in which ϵ_0 and μ_0 do not appear. Thus if we use merely Eq. (21) we have

$$n=c/v=c(\epsilon\mu)^{\frac{1}{2}}/k \tag{25$'$}$$

as the general expression for n, holding in any system of units. There is a special form of Eq. (25′) for each separate system of units. These special forms can be further simplified, in the case of ordinary light, since for such waves μ has the same value as in free space, to a high degree of approximation. This is due to the fact that the molecular dipoles, which give the medium its characteristic value of μ for a steady magnetic field, are not able to orient themselves rapidly enough to follow the high frequency field of a light wave. Hence the medium reacts to the light wave essentially as if the magnetic dipoles were not present. We therefore get the following table for n, which of course always has zero dimensions, since it represents the ratio of two speeds. In order to make quite clear the fact that the various formulas apply only to the system stated at the left, I use in Table II the subscripts s and m. To be strictly logical, the subscript g should be used for the Gaussian system, but we have seen that there is no possible distinction between ϵ_s and ϵ_g, nor between μ_m and μ_g, so that as a practical matter only the s and m subscripts are required. In the last column of the table are noted the relations used in getting the specific formulas from the general formula (25′), together with the value of ϵ in free space, in which n is by definition unity.

TABLE II.

	Index of Refraction n		
System	n (all waves)	n (light waves)	Remarks
e.s.	$c(\epsilon_s\mu_s)^{\frac{1}{2}}$	$\epsilon_s^{\frac{1}{2}}$	$k=1,\ \mu=c^{-2}$ ($\epsilon_s=1$ in free space)
e.m.	$c(\epsilon_m\mu_m)^{\frac{1}{2}}$	$c(\epsilon_m)^{\frac{1}{2}}$	$k=1,\ \mu=1$ ($\epsilon_m=c^{-2}$ " " ")
Gaussian	$(\epsilon_s\mu_m)^{\frac{1}{2}}$	$\epsilon_s^{\frac{1}{2}}$	$k=c,\ \mu=1$ ($\epsilon_s=1$ " " ")

Without making specific references at this point, I may note that the general formula for n is commonly given as $(\epsilon\mu)^{\frac{1}{2}}$, even in texts that describe only the e.s. and e.m. systems and make no mention of the Gaussian system. This is merely a further proof that writers normally employ the Gaussian system, whether or not they realize the fact.

In the preceding discussion incidental reference has been made to some of the sources where specified parts of the foregoing relations are given explicitly and correctly. A very incomplete list of such references is as follows.

Planck,[4] pp. 16–18, gives a definite statement of the relative values of ϵ_0, μ_0 and k, in the three systems we have discussed, although his method of derivation differs from ours. A much older and widely used source of information is the text by Abraham-Föppl,[21] to which reference was made in footnote 7. In Vol. I, pp. 212–216 and 257–262, of this work there is given so definite a statement of the subject matter of the present paper that it is surprising that any subsequent errors or ambiguities should have arisen. A recent discussion of the subject is that by Page.[15] The excellent text by Abraham[8] has also been mentioned; this book, however, uses exclusively the Gaussian system (see p. 153) and therefore does not consider fully the interrelations of the various systems.

I close this paper with a few specific references to errors or ambiguities in textbooks, not because of any desire to criticize, but because it seems necessary, in order to make the matter really clear, to note specifically some of the forms of statement that are very misleading, if not incorrect, as well as those that are quite correct. Let us start with Starling,[1] a writer who, in the seventeen years between the appearance of the first and the fifth editions of his text, does not seem to have changed his point of view on the matter of dimensions. On page 386 (5th ed.), he states

"It is usual to consider, for practical purposes that empty space has unit magnetic permeability and dielectric constant, but it should be noted that these units are really arbitrary, and until we know more about the properties of the luminiferous ether we cannot say what their absolute dimensions may be.

"Starting with our definition of unit pole on one hand, we have built up a system of units for electrical and magnetic quantities, all of which involve the dimensions of μ which is called the *electromagnetic system*, and, with the definition of unit electrical charge, on the other hand, the

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[21] M. Abraham and A. Föppl, *Theorie der Elektrizität*, 3rd ed., 1907.

resulting system on which all the quantities involve the dimensions of ϵ is called the *electrostatic system.* Both of these are absolute systems, by which is meant that the magnitudes of the units are derived directly from the centimetre, the gramme, and the second, μ and ϵ being taken to be numerically equal to unity."

I have already considered the subject of "absolute dimensions," but there are other portions of this quotation that deserve comment. It seems to me that this is a perfect example of the practise noted by Abraham[17] of the use of the electrical side of the Gaussian system, but with the designation, the e.s. system. Thus the e.s. system necessarily involves both ϵ and μ, and to each of these quantities is arbitrarily assigned the dimensions stated in Table I. The dimensions of ϵ appear explicitly, however, only in certain formulas, and these are just the formulas that constitute the electric side of the Gaussian system. In other formulas the dimensions of μ appear explicitly, and if one is actually using the e.s. system, μ must be given the dimensions $L^{-2}T^2$ and the magnitude c^{-2} in free space. If, however, one is using the e.m. system, these latter formulas are identical with the magnetic side of the Gaussian system, and μ has zero dimensions and is unity in free space. That Starling is really using the Gaussian system, although he makes no mention of it, is proved by his statement "μ and ϵ being taken to be numerically equal to unity." This, as Table I shows, is true *only* for the Gaussian system.

It is not, however, possible to give a consistent interpretation to Starling's treatment, for on p. 391 he writes $1/(\epsilon\mu)^{\frac{1}{2}}$ = velocity, and on p. 395 he states that this velocity is 3×10^{10} cm/sec. in free space. From Eq. (21) or (22), and Table I, we see that these last statements are true for the e.s. or the e.m. system, but are not true for the Gaussian. Hence there is a definite contradiction between the statement of p. 386 and those of pp. 391 and 395.

Let us now consider Gilbert's *Electricity and Magnetism*,[19] one of the very few places where, as already noted, the entire e.m. system is used. On p. 463 he writes "$v=1/(\epsilon\mu)^{\frac{1}{2}}$, where both μ and ϵ are measured in the electromagnetic system." This is a correct statement, since k in Eq. (21) is unity on the e.m. system. On p. 464, referring to the velocity of waves of ordinary light, he writes "$\mu=1$ very nearly," and this is also true on the e.m. system, as we have noted in connection with Table II. He then, however, gives the index of refraction n as

$$n=\frac{1/(\epsilon_0\mu_0)^{\frac{1}{2}}}{1(\epsilon\mu)^{\frac{1}{2}}}=\epsilon^{\frac{1}{2}}.$$

The ratio in this equation is correct, in accordance with Eq. (25), since it expresses the velocity in vacuum divided by that in the medium, both expressed in e.m. units. But his $\epsilon^{\frac{1}{2}}$ should be $c\epsilon^{\frac{1}{2}}$, as Table II shows, since $\epsilon=c^{-2}$ in the e.m. system, for free space. It is evident that at this point in the text Gilbert unintentionally changes to the e.s. system, for he next quotes $\epsilon^{\frac{1}{2}}=8.9$ for water, a result that is true in the e.s. system, but not in the e.m. system.

As a final quotation from the literature,[22] I give an example of the confusion likely to arise when one does not distinguish between dielectric constant and specific inductive capacity. Page and Adams,[16] on p. 44, state "The quantity ϵ is known as the specific inductive capacity of the dielectric, or the dielectric constant. Since D, E and P have the same physical dimensions, $\epsilon\cdots$ are pure numbers." The reference to D, E and P shows that ϵ is being used in the sense of the dielectric constant, and the statement as to its dimensions is true for the e.s. and Gaussian systems, but not for the e.m. system. As a matter of fact these authors actually reserve the symbol ϵ (their κ) for the *dielectric constant measured in e.s. units.* Thus in place of our Eq. (5″) they write (p. 439), $D_m=(\epsilon/c^2)E_m$, which is correct, according to our Eq. (23), provided that ϵ stands for ϵ_s. But then, on p. 443, they say "Finally, ϵ and μ, being pure ratios, are the same in all systems of units." This statement is technically correct, for since they reserve the symbol ϵ for ϵ_s and the symbol μ for μ_m, these quantities are, in fact, without dimensions and can be thought of as obtained from pure ratios. But it seems to me that the statement is very misleading, since ϵ is constantly used in the text in the sense of dielectric constant, and that quantity, as we have seen, is not a pure ratio, and does not have the same value in all systems

[22] Additional errors that were common in the older literature are mentioned by Bond (reference 3).

of units. Moreover it is not explicitly stated that they reserve the symbol ϵ (their κ) for the e.s. system, and the remark that it is the same in all systems of units seems to imply that it is *not* so reserved.

In concluding this paper I should like to make a more personal remark. It is evident to me now that there are only occasional statements in the literature that can be classed as definitely incorrect. When, however, I was trying to get this matter straight in my own mind, I constantly came across statements that seemed to be incorrect or to contradict other published statements. Closer analysis shows that in most cases such statements can be defended as technically correct. On the other hand, if my own experience constitutes any evidence, it would appear that these statements easily lend themselves to misinterpretation, so much so that I have found that many other persons with whom I have discussed this matter have drawn from them equally false inferences. It is to be hoped, therefore, that in the future all elementary and also advanced textbooks will follow the very clear treatment of the subject that can now be found in a few selected places in the literature.

Physics in Relation to Medicine*

This report was prepared by Professor William J. A. Bliss, Doctor H. B. Williams and Doctor Paul E. Klopsteg in 1922 for the Education Committee of the American Physical Society and was published by the Society in 1923. In obtaining material for the report, the compilers had the cooperation of Professors H. W. Farwell, F. K. Richtmyer, H. B. Lemon, G. N. Lewis and F. C. Blake, all of whom have had experience in teaching premedical students, and they also had the assistance of various other physicists and medical men.

In the eleven years since the report appeared first, both the science of physics and the art of teaching it have made great progress, but the relation between them is the same in principle now as then. Long before that time, the useful content of physics had become so great as to preclude the possibility of presenting it all in a one-year course. The first problem in planning such a course, therefore, was already that of selecting the most valuable parts of the science and omitting, however regretfully, many other topics of recognized value. The principles underlying this selection, rather than the results of it, were the primary concern of the committee in writing this report. Today the wealth of material from which to select is even greater, and our courses correspondingly better. But in the opinion of the present committee the principles of selection of topics are practically unchanged, and the excellent statement of these principles by the previous committee applies as well today. In view of the scarcity of copies of this report, therefore, and in view of the number of interested teachers who have not seen it, the present committee deems it a first duty to recommend its reprinting in *The American Physics Teacher*.—David L. Webster, *chairman*, Committee on the Teaching of Physics for Premedical Students of the American Association of Physics Teachers.

I. Importance of Physics to the Progress of Medicine

In the middle of the last century, largely through the influence of Liebig, a great impulse was given to the application of chemistry to medicine and physiology, and for a long time physics was by comparison neglected. Such phenomena as diffusion and capillarity were recognized as important, as were obvious applications of a few other parts of physics, for example, to sight and hearing, and this led to the requirement of some small preparation in physics for the study of medicine. This was gradually increased with the growth of laboratory equipment in medicine, applying all branches of physical measurement. The present position of physics, however, is not simply the result of the natural spread of similar applications. It is much more revolutionary. The rising importance of physical chemistry; the application of thermodynamics to chemistry; the extraordinary development of physics in the last quarter century, of which the discoveries arising from x-rays and radioactive transformations are only a part; all these have placed physics in a fundamental position as regards science in general. Thus physics has become doubly important to medicine; first through the growth of its applications, of which some examples are enumerated below; secondly, and fundamentally, because it is essential to an understanding of other sciences,

* Sections I–III appear in this issue. The remainder, Sections IV–VI, will appear in the September issue.

the medical importance of which has been longer recognized.

Naturally a strong demand has developed, not only for increased preparation in mathematics and physics for the student entering the medical school, but for increased participation of physicists in medical research. While the advance of medicine in the last century may be chiefly attributed to chemistry, biology, bacteriology, and kindred sciences, the key to the future seems to be sought more and more in physical chemistry and physics. A few of the applications of physics to medicine may be cited as illustrations.

General Physics. Inertia, moment of inertia and elasticity are of importance to the physiologist in relation to properties of instruments used in various types of measurement, such as the measurements of hemodynamics. In order to make accurate measurements or to know the accuracy of a measurement which is being attempted, connecting mechanical movement with time, knowledge of the natural period and damping forces of the apparatus used is needed. The biologist must often design his own instruments and develop his own methods; in order to do this successfully, he requires enough theoretical knowledge to predetermine the properties which a particular design and choice of materials will give. There are plenty of examples in biological literature of the enormous waste of time and effort which lack of such knowledge has caused.

Construction, care and reading of barometers and correction of barometric readings to standard conditions are methods constantly applied in biological work. Diffusion of gases, partial pressures, solution of gases in various solvents and the relation of these phenomena to pressure and temperature changes are of enormous theoretical importance in biology and should be well understood.

The phenomena of osmosis, adsorption, etc., are of the utmost importance in the formulation of biological theories. Such subjects as digestion, secretion, excretion and the like cannot be discussed without some knowledge of them.

Sound. The fact that we have a special sense organ for the perception of sound, an organ whose integrity is a matter of great practical interest, is of itself an indication of the importance of a knowledge of the physical nature of sound.

The investigation of the normal function of the ear and of its pathology requires first of all thorough knowledge of the underlying physics. One might mention such investigations as the relation of phase differences at the two ears to ability to locate the direction of sounds, and the studies of the relation between frequency of the sound and the minimum amount of energy required to produce the sensation of hearing, as examples of physiological studies requiring knowledge of physical acoustics. Moreover, the physician constantly employs his ears in the diagnosis of diseases of the heart and lungs, and particularly in connection with the use of aids to hearing and devices for intensifying and recording these sounds he needs precise knowledge of acoustics.

Heat. The body of a warm-blooded animal performs the functions of a thermostat, provided with various chemical and physical means for regulation. The various reactions which go on within it seem to require this nice regulation for the efficient operation of the mechanism.

The energy exchanges between the living body and the food which constitutes its fuel have been made the subject of careful investigations, which are still going on. Precise studies of such changes in man were made with Professor Atwater's respiration calorimeter, the successful development of which, for the heat measurements, was largely due to the cooperation of a physicist, Professor E. B. Rosa. It is particularly desirable to secure similar knowledge of such energy changes in disease, and calorimeters on like principles have now been applied to such problems also; for example, diabetes, in which the normal ability to utilize carbohydrates as fuel is impaired; typhoid fever, in which the maintenance of the body at an elevated temperature over prolonged periods requires the expenditure of greatly increased amounts of energy; and various other conditions. The entire problem of sustained animal life depends upon that of nutrition, which, in turn, involves heat energy studies. If we ever come to a clearer understanding of the problems of secretion, assimilation, production of muscular energy, and others of a fundamental nature, it seems likely that no small part in the advance will be played by a study of the energy relations. From theoretical aspects a knowledge of thermodynamics seems highly desirable for the biologist.

Of less fundamental character, but no less important, are such matters as thermometry, including mercury-in-glass, electrical resistance, and thermocouple thermometry, knowledge of stem corrections, etc. These are necessarily involved, in some form, in all calorimetric work, in investigations of fever, etc. Knowledge of the laws of conduction and radiation of heat is desirable in connection with apparatus used by biologists, as well as in consideration of the living organism itself.

Light. The effect of light in modifying the course of chemical reactions is almost too well known to need comment. The relation between the growth of green plants and sunlight has long been known. A more recent development is knowledge of a direct relation between exposure to light of certain wave-lengths and the prevention of rickets, a disease of childhood. One of our most important sense organs is the eye. A knowledge of geometrical optics and of various optical instruments is absolutely indispensable to the ophthalmologist. Optical instruments of many kinds are in use by biologists. Photography plays a part of increasing importance in scientific investigation. The spectroscope has long been used in chemical investigations. The microscope is preeminently the biologist's own instrument. The spectrophotometer promises to become a powerful instrument of research in biological chemistry.

The problems of physiological optics have been but little cultivated by physiologists since the time of Helmholtz, and

many of these should be made subjects of research, notably color vision, vision itself, the part played by the ocular pigment and the visual purple, etc. In recent years physicists concerned with optics have been forced to make studies of some of these physiological problems bearing on the use of the eye in physical measurements, for example, studies of visual luminosity curves in connection with photometry of light of different wave-lengths. The physiologist who undertakes such problems as those mentioned above must of necessity be well informed on these investigations and on physical optics in general. There is great need of a course in ophthalmology of such a comprehensive character as shall really fit the graduate for all the various exigencies of practice. It should naturally include the pathological and surgical aspects of the subject, and also thorough and adequate instruction in geometrical optics and physiological optics. There are few men at the present time competent to give really adequate instruction in the last, and, so far as the committee is aware, no medical school offers to a graduate in medicine a comprehensive course comparable with that outlined above.

Electricity and Magnetism. There is perhaps less reason to direct attention to the need for knowledge of these subjects in connection with biology and medicine. Few persons in any walk of life today can carry on their work without some elementary knowledge of electrical phenomena. Electrical instruments in great variety and for many purposes find application in the study and practice of medicine. The use of x-rays for making shadow pictures of inaccessible parts of the human body is familiar to all, and these rays together with the radiations from radium and other radioactive substances are used in the treatment of certain diseases. This brings with it the need of precise measurements, and in some biological laboratories at the present time will be found such devices as ionization chambers with their accessories and even x-ray spectrometers.

The increasing tendency to apply the methods and point of view of the physical chemist to biological problems has made the determination of hydrogen ion concentration by electrical methods a matter of daily routine in many biological laboratories. The electrolytic conductivity of the body fluids is another subject applying physical chemistry and physics. The electrical action current of muscles has been a well-known physiological phenomenon for years. Until recently it was considered as of academic and theoretical interest only. Within a decade the measurement of the action current of the heart has come to be a routine method of diagnosis in many hospitals and clinics. This has been made possible through the development for this specific purpose of a special instrument, the string-galvanometer. It is significant that this instrument was developed not by a physicist or engineer, but by a physiologist and physician, Professor Einthoven of Leyden. The history of this development indicates very well the advantage of an adequate knowledge of physics and mathematics on the part of the biologist.

More recently the development of the three-electrode vacuum tube has provided a powerful tool of research. The possibilities of this instrument were promptly recognized by several biologists, and it is likely it will be extensively employed in biological investigations. One might mention recent researches by Forbes and by Bovie and Chaffee at Harvard, as illustrating applications of vacuum tube amplifiers to biological problems.

It seems highly probable that the photoelectric cell will find a useful place in biological research before long. Quite apart from the use of photoelectric apparatus in research, the phenomena of photoelectricity have an important bearing on optical-chemical-biological theory.

This outline is intended to be suggestive. Any attempt to catalog the manifold inter-relations between physics and medicine in a thorough and complete fashion would attain the proportions of a volume. The ideal to keep in mind, in preparing a student to apply physics to the problems of medicine and biology, is not that he be given special facility in this or that branch of physics, which may seem to bear a definite relation to a particular phase of his subsequent work. The aim should rather be to teach the *subject* in sufficient generality and with sufficient thoroughness to enable the student at any time to extend his knowledge along any special branch of physics as the circumstances of his later work may require. No one can tell what the medicine of even 1930 may be like. Science grows and changes and the prospective scientist must be so trained that he may be able to grow and change. Who could have foreseen in 1880 the lines along which physics would be advancing in 1920? Who knows but that the medical student of 1940 may be guided in his theories of life phenomena by a theory of atomic structure so far perfected as to be of great service in the contemplation of the complex problems of biology?

It is hardly to be expected that students preparing for medical study or even for a career of investigation in biological fields will, at the present time, undertake anything like the preparation in physics which would be regarded as suitable for a prospective investigator in physics. In chemistry, the preparation of the present-day biologist is often as good as that of any professional chemist. This is as it should be, for the enormous importance of chemistry in biological investigations has been demonstrated. That physics may be able to furnish the biologist (and the chemist also for that matter) with most powerful methods of research, theoretical as well

as experimental, is beginning to be recognized. The demand for increased training in physics will eventually come from the students themselves. When it does, the amount need be limited only by their ability to assimilate and use it. It is necessary that teachers of physics should be aware of the many points of contact between their subject and that of the biologist, and that workers in both fields should see to it that students are made aware that physics for the biologist is no academic luxury, that it is a necessity, of which, perforce, he will be unable to secure enough, and of which he should secure so much as will enable him to obtain a foothold and advance by his own efforts, when time and opportunity shall have indicated to him along what line of physical theory or technique he will find most assistance in the biological problems he undertakes to solve.

II. Physicists for Medical Institutions

While more adequate training in physics for medical men in general seems essential, it must be recognized that mastery of that science cannot be expected of them, and that at present even a sound working knowledge is rather unusual. There is, therefore, urgent need for advice from trained physicists, constantly available in medical institutions, and for the cooperation of physicists as such in medical research. It is, therefore, desirable that there should be one or more physicists as part of the regular staff of such an institution. If it is connected with a university, these men might be members of the department of physics. Or, if more convenient, they might form a separate group, as is usually the case with physiological chemists, for example. But, in that case, special care should be taken that they preserve the closest relation with the department of physics, both for the coordination of instruction and research by the two groups, and in order that the men engaged specially upon medical applications of physics may keep fully up with the science as a whole. It is obviously necessary that they should remain good, progressive physicists, just as it is desirable that they should have had initially a broad, sound training in pure physics, rather than one that has specialized too early in existing biophysical methods.

To be qualified for the work here referred to, a physicist should possess experimental ability of a high order and ingenuity in the application of a wide range of physical methods; but, while these qualities are essential, the great problems need men who can combine them with the ability to apply physical theory to the phenomena of medicine. Such a physicist should also be cooperative and interested in the problems of others, rather than inclined to shut himself up in his own personal investigations, and, as a detail of organization, it is important that he should not be so closely identified with some one department that he will be regarded as its particular property. He should by all means be provided with a laboratory equipped both for research and for instruction in the use of physical methods appropriate to the work of the institution, but he should be ready to leave it when wanted to give help and advice. In other words, the situation calls for men who cannot only carry on independent research, but who can also supplement the lack of knowledge of physics of their colleagues. In view of the ignorance of the physicist as to the problems of biology and medicine, most men called to such positions would have to begin with such collaboration.

III. Study of Physics in Preparation for Medicine

The attempt to provide better instruction in physics for medical students, whether in school, college, or the medical course, leads to a dilemma, between what appears to be the urgent need of more adequate preparation and serious objection to any further lengthening of the medical and premedical course. A distinguished professor of clinical medicine says that a student in his classes should have a preparation in physics and mathematics equal to that which must precede a graduate course in physics. An equally noted professor of physiology thinks that it would be easier to teach an electrical engineer the medicine necessary for a study of physiology than to teach the present medical graduate the necessary physics. Opposed to these are the statements of wise and experienced authorities on medical education who urge that the requirements for a degree in medicine are already too high: that they deter men from entering the profession. It has

been stated that the number of medical graduates is less than the loss by death and retirement, but accurate statistics gathered by the Council on Medical Education of the American Medical Association prove that this is not the case. The lack of physicians in country districts appears to be a question of distribution rather than total numbers; and the remedy is to be sought in improvement in the conditions of country practice rather than in the medical curriculum.

Assuming that it would not be advisable to increase the total requirements beyond the present standards of the best medical schools, more time for physics must be sought by lessening that allotted to some other study, but here also the outlook is not encouraging. The doctor, like the lawyer or the clergyman, should be a man of liberal education, to broaden his understanding and sympathy with his patients and to command their confidence. His profession is rooted in the classics by history and terminology and he needs modern languages to keep up with its progress. Institutions which require two years of biology might perhaps reduce this amount, in view of the fact that the medical school can meet a deficiency in this better than one in physics. It is also possible that there is unnecessary repetition of similar details in the first course in chemistry and that this work might be condensed with advantage. The relief from these changes would, however, be small, and though they were suggested by medical educators of high standing and experience, they were opposed by others who felt that the doctor is resorting too much to the laboratory, and getting out of personal contact with his patients. They feared that greater emphasis on physics in the curriculum would lead to an overestimate of the value of physical instruments in medical practice. Such a tendency might be avoided if the emphasis in the course in physics for medical students is placed on the teaching of pure physics as a basis for the medical sciences, rather than on any narrow technical application.

The best way to meet the difficulty is to provide two grades of preparation in physics for the study of medicine. The vast majority must, at least for the present, be limited to the "one year of college physics" now generally required. A few, marked by special ability in mathematics and physics, but desiring to apply these to medicine, may add a second course, which might be accepted by the medical school in lieu of some of the required biology. It is not intended here to suggest that students preparing for medicine should choose during their college course whether they will enter practice or devote themselves to research, but merely that each should follow his natural inclination as between a second year of biology and more physics, and that the medical school should admit the alternative, in the belief that a limited number of men so prepared will be of value in the medical field, and that the majority will choose the biology. The committee, therefore, strongly recommends that an elective course suitable for such men should be provided, and should normally be taken in the third or fourth year of a four-year college course. It would be difficult to provide for this option in a two-year or three-year college course, but if the medical school could condense some of its work in anatomy and kindred subjects, it might be possible to introduce it as an elective in the medical school. In addition to the required course and elective already mentioned, there should be provided, in the medical school, instruction in physics as directly applied to medicine, as part of the duties of the physicist recommended in another section of this report. Two such courses, Biophysics 1 and 2, were given with gratifying success at The Johns Hopkins Medical School in the first semester of 1921–22.

I LOVE fools' experiments. I am always making them.—CHARLES DARWIN

The Rôle of Positrons and Neutrons in Modern Physics*

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POSITRONS are atoms of electricity, and neutrons are atoms of mass. Hence, in order to discuss the rôle of these atoms in modern physics it is necessary to review the rise and development of atomism in physics.

The idea of atomism is as old as recorded history. Since the earliest times of which we have any extensive record, philosophers have considered the view that all matter is made up of indestructible and indivisible parts which the Greeks called *atoms*. In the fifth century B.C. Leucippus founded his school at Abdera and expounded the atomic theory of matter as an explanation of the infinite variety of the aspects of nature. His more distinguished pupil, Democritus, developed and elaborated this theory until it resembled, in many respects, the views which are held today.

Democritus maintained that there exist atoms, and an empty space, or vacuum, in which they can move around. Some of his contemporaries found difficulties in the conception of an empty space, and wished to have matter with a continuous structure. Democritus claimed that the atoms were indivisible, whereas others were unable to conceive of true indivisibility. In these difficulties there are many problems of considerable subtlety which have persisted to the present day; but most of us are little interested in such subtleties of reasoning and demand more practical considerations. Of recent years, however, the question of indivisibility has come into some prominence in connection with the quantum theory. This connection I shall mention a little later. At this point, however, I may call attention to the nature of the dilemma.

If I consider a piece of paper, it is evident that I can cut or tear it into two parts. It is also evident that I can take each part and again cut it into two pieces. This process I can repeat a number of times until the pieces are so small that I cannot hold them in one hand while I cut with the other. Then I can put the pieces under a microscope and can use a very sharp knife to divide them. The question arises as to whether I can always cut a piece into two smaller pieces. At first thought one is tempted to assert that of course this is always possible. But it is certainly true that for any given knife there is a limit beyond which it is not possible to go; when the pieces of paper become smaller than the thickness of the edge of the knife, it is not possible to use that particular knife to cut the paper. Similarly for every other cutting device, there is a limit beyond which it will not go.

One may object to this type of argument by saying that it is not necessary to actually cut the paper in order to think of the parts. One can simply imagine the cutting to be performed. This has been a rather common point of view and it seems natural enough. The contrary point of view is, however, that it is meaningless to imagine something that cannot possibly be carried out. In addition, if this type of imagination is permitted, it becomes necessary to conceive of the possibility of dividing the piece of paper an infinite number of times. Now while we tend to speak very casually of infinity, a careful thinker, and the Greeks were very careful thinkers, has some difficulty in thinking of a process being repeated an infinite number of times.

There are then two possibilities: either matter is made up of atoms which cannot be subdivided, or else matter can be divided indefinitely. In case we think of atoms we immediately want to ask what they are made of and what is inside of them; but in so doing we contradict the original assumption. In case we do not like indivisible atoms it is necessary to think of infinite divisibility. I shall return later to the modern point of view toward this dilemma.

The atomic theory is very attractive from one point of view which seems to have recommended it strongly to the ancients. If one casually observes the world around him, the most striking

* A lecture delivered to the California Teachers' Association, Southern Section, December 20, 1933.

characteristics are its infinite variety and its eternal change. The impressiveness of this fact has caused some philosophers to hold that change is the one fundamental thing in the universe. Although this may be true as a general statement, it does not provide a fruitful basis for the construction of a scientific description. In order to classify things or phenomena, it is necessary to discover some constant features, some invariable elements. In fact one might say, with a good deal of accuracy, that the whole of science consists in the search for permanent or invariant things. The eternal, indivisible, atoms furnished these necessary elements; in the midst of a universe of infinite variety and change, a few varieties of atoms remained simple and permanent.

The ancient atomists held that the varied appearances of things are due to the various ways in which the atoms can be put together. They believed that all atoms were essentially similar, and that although they might differ in size and shape, they were all composed of the same primordial stuff. Their atoms were naively-imagined, small-sized pieces of solid body whose properties are those known to our ordinary senses. With these they proposed to build a purely mechanical theory of the universe such as would have appealed in principle to many an eighteenth or nineteenth century philosopher.

These views of Democritus and the school of atomists were dominant for over five hundred years. Shortly after the beginning of the Christian era, however, they began to wane, and by 200 A.D. they had been rather definitely discarded in Europe. The conceptual difficulties of indivisibility and of empty space had been too much for the minds of the Europeans.

But although atomism apparently disappeared in Europe, it was not entirely dead; like so many other parts of the science of the Greeks, it was preserved in the Arabic schools and in occasional obscure manuscripts. During the seventeenth century the idea became more and more attractive to natural philosophers, and 1650 may be taken as an arbitrary date which places the return of atomism. Atomism provided a convenient explanation of many facts: the mixture of different substances and the solution of one in another could easily be pictured as mixtures of corpuscles; the diffusion of one substance into another and the rapid propagation of odors were easily understood if all matter was corpuscular. Since that time, atomism has continued to increase its hold upon Western science, but has itself undergone very extensive changes.

The beginning of the nineteenth century saw the development of the modern chemical atoms and molecules. It witnessed the appearance of mass, instead of size and shape, as the characteristic feature of atoms. The laws of chemical proportion were interpreted by Dalton in terms of atoms of the chemical elements. When he proposed his theory the number of elements was relatively small, but it immediately started to grow. This growth was distressing to some, in that it destroyed the simplicity of the picture. As an attempt to return to a more simplified idea, Prout suggested that all atoms were combinations of hydrogen. This suggestion required the atomic weights to be integral multiples of the weight of hydrogen; but it was definitely established, after a good many years of work, that no such simple situation existed. The nineteenth century may be regarded, however, as the time of the development of chemical atomism. The atoms were identified and weighed. Their properties in combination with each other were studied and classified, and the whole more or less culminated in the periodic table of the elements proposed by Mendeleef. By the end of the century there were only a few who would seriously deny the reality of chemical atoms.

These atoms were, insofar as chemical methods went, indivisible particles of the elementary substance. One definition of such an atom is that it is a particle which cannot be divided by chemical means. Since the term atom has been used so much to designate them, it is likely to cause some confusion when the term is used in its original sense. I shall attempt to avoid this ambiguity by speaking of *chemical atoms* in the sense in which the term is usually used and with which you are all familiar, and shall reserve the term *atom* for a particle which is indivisible by any means whatever.

Although the end of the nineteenth century saw the general acceptance of the chemical atom as the building stone of all matter, it also witnessed its break-up into the more elementary

atoms which we know today. The first of the constituent particles which were discovered was the negative electron. The sense of the term electron has passed through many vicissitudes, but has recently been restricted to the designation of the elementary unit of negative electrical charge. It appears now, however, that in this sense it must be qualified, and so I shall speak of the *negative electron.* The discovery of this electron grew out of the various experiments on the conduction of electricity through gases, which were performed by a large number of different persons, but the discovery is generally attributed to J. J. Thompson, who first determined its properties with some accuracy.

Since the negative electron is one of the most fundamental things in modern physics I wish to explain briefly the nature of some of the evidence for it. If two electrodes are sealed into a glass tube and most of the air is removed, an electric discharge will pass between the electrodes with relatively little difficulty. If the pressure is reduced sufficiently, a fluorescence appears on the glass opposite the negative electrode, and some luminescence can be seen in the gas itself, stretching from the cathode to the walls. It is evident from the behavior of the discharge that something comes from the cathode and strikes the walls. If an object is interposed it casts a sharp shadow on the glass. The luminous beam can be bent, and the fluorescent spot can be moved by a magnetic field; the beam is bent at right angles to the magnetic field such as would be expected if it were a stream of electrified particles, and it is bent in the direction to indicate a negative charge upon the particles. It is also possible to deflect this stream with an electric field, and a suitable electric field can be made to oppose the action of a magnetic field and just annul it. If one calculates the path of a particle given off from the cathode, through an electric and a magnetic field, it becomes evident that the values of the two fields for which the particle describes a straight line depends upon the ratio of the charge to the mass of the particle. Hence a measurement of these fields gives a measurement of this *specific charge.* During the years 1897 to 1907 J. J. Thompson measured this quantity and found it to be the same for all of the particles no matter from what kind of cathode they came or what the nature of the gas in the tube. Furthermore, and still more startling to the discoverer, this specific charge was 1840 times the specific charge of a hydrogen ion as determined from Faraday's laws of electrolysis. This meant either that the charge carried was very large, or the mass of the particle was very small. The latter proved to be the correct interpretation. This, then, gave the first intimation that the real atoms were much smaller than the chemical atoms, and started the twentieth century development of the theories of the electrical nature of matter.

Since these small negative electrons can be obtained from all kinds of matter it must be concluded that they are constituents of all matter, and, hence, since the atoms are ordinarily electrically neutral, there must be a positively charged constituent. From experiments, on deflecting streams of positively charged ions in electric and magnetic fields, it was found that the positive constituents are much more massive than the negative electrons. The form of the positive constituent was determined in 1911 by Rutherford who found by experiments on the scattering of α-particles that they are small but massive positive nuclei. These nuclei contain practically all of the mass of the chemical atom, but only the positive charge. The nucleus of the hydrogen atom has been called the *proton,* and the nuclei of all other elements can be regarded as composite particles which contain protons.

One of the difficulties with the theories of atomism had been the apparent impossibility of isolating and studying a single atom. It had been necessary to deal with tremendous numbers of atoms, so that there were always a few persons who were willing to treat the atomistic theory as a convenient working hypothesis, but were unwilling to ascribe to it any great degree of reality as a description of matter. This difficulty was partly overcome by the invention of the spinthariscope, which made visible the impacts of single α-particles from radioactive substances. But the tremendous advance in this direction was made in 1911 by C. T. R. Wilson in the Cavendish laboratory at Cambridge. He developed the so-called Wilson cloud chamber in which can be made visible the tracks produced by single particles of many kinds. This instrument has been the principal means of investigation in the recent work which has led to the discovery of the positive electron and the neutron. It was considered such an important development that the Nobel prize was awarded a few years ago to its inventor.

Fig. 1 shows the essential parts of the apparatus. The chamber, A, has a glass top and glass cylindrical walls, and is closed on the bottom by a piston. The air is pumped out of the bulb C, and when this bulb is connected with the under side of the piston, the air rushes into the bulb and the piston comes down quickly. This causes the air in the chamber A to expand. If the chamber A contains saturated

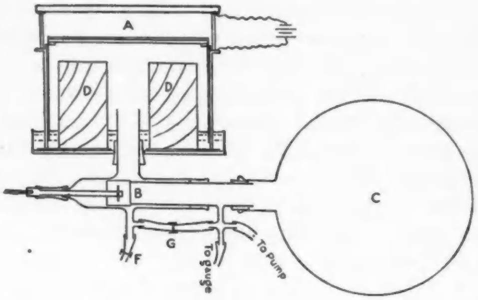

FIG. 1. Diagram of a Wilson cloud chamber. [C. T. R. Wilson, Proc. Roy. Soc. **A87** (1912).]

FIG. 2. Alpha-particle tracks. [C. T. R. Wilson, Proc. Roy. Soc. **A87** (1912).]

water vapor, some of it will be condensed by the cooling produced on expansion, and there will be a uniform cloud of small water droplets throughout the chamber. If, however, the expansion is not too great, the cooling will be small and the water will condense only if there are nuclei of some sort present to start the condensation. If dust particles are present in the air in the chamber, a drop of water will condense upon each of them even when there is no general cloud; these particles and their surrounding drops of water will then settle to the bottom of the chamber and after a few expansions the air will be so clean that no more condensation will take place. Nuclei for condensation can be provided, however, by ionization of the air molecules. If an electron is shot into the chamber it ionizes the gas molecules along its path, and so produces a trail or a track of ions. Then when the air expands and cools, water droplets condense upon these ions and the track can be seen and photographed.

Fig. 2 shows a photograph of the chamber when a bit of radioactive substance is placed in it. The photograph is taken from the top so that one sees the circular chamber and, at the bottom, the small needle which carries the radium on its end. The tracks are due to α-particles from the radium. The disintegrating radium turns into radon, which is a gas, and this gas then spreads throughout the chamber and itself also gives off α-particles; tracks due to the latter can be seen in the upper part of the picture.

I have spoken a number of times of α-particles without specifying their nature. An α-particle is a particle which has a positive charge equal to twice that on a proton and a mass which is roughly four times that of a proton. It is in fact a helium nucleus, and if the α-particles from radium are collected and allowed to capture electrons, which in fact they cannot be prevented from doing, the result is merely helium gas. It has never been found possible to disintegrate α-particles, and so from a strictly experimental standpoint they should be considered as elementary atoms. It is generally believed, however, that they could be disintegrated if sufficient energy could be applied in the right way, and so they are not usually treated as elementary particles.

In Fig. 2 it is of interest to notice that the tracks are all very roughly of the same length. Of course they start out in all directions and so many are fore-shortened. This property makes possible the use of the length of the track to determine the energy or speed of the particle. It can also be seen that the thickness of the track is not the same at all points. At the beginning, where the α-particle is going fastest, the track is rather thin because fewer ions are produced. As the particle loses energy and hence speed in producing the ions it becomes more effective in their production so that the track becomes thicker. Right at the end there is occasionally a kink which shows that the particle has become slow enough to be deflected by approaching near to a molecule of air. Most of the tracks show occasional deflections where the particle has passed near an atomic nucleus, whereas some show very sudden breaks. Fig. 3 shows an enlargement of the ends of two tracks. In one of them the α-particle has collided almost directly with the nucleus of an atom of air, and

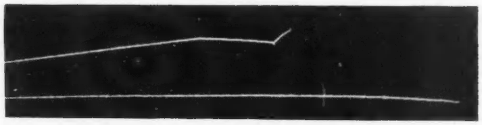

FIG. 3. Enlargement of two α-particle tracks. [C. T. R. Wilson, Proc. Roy. Soc. **A87** (1912).]

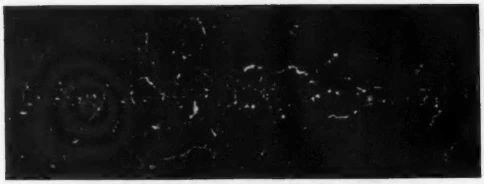

FIG. 4. Tracks due to negative electrons ejected by x-rays. [C. T. R. Wilson, Proc. Roy. Soc. **A104** (1923).]

the track produced by the recoiling nucleus can be seen. It is by observing events like these that it is possible to confirm the conclusions reached by Rutherford that the nuclei of atoms are very small, since only when the α-particle and the nucleus are very close together can such a sharp deflection take place. Fig. 4 shows the picture which is obtained when a beam of x-rays is passed through the chamber. There are a great many tracks, this time due to negative electrons. The tracks are not so thick since the electrons do not produce so many ions per unit length of path, and they are very crooked since the negative electrons have so little mass compared with the atomic nuclei near which they pass that they are easily deflected. The little blobs which appear occasionally are due to the electrons which are shot out of atoms by the impact of the initial electron.

The result of the invention of the Wilson chamber has been the conviction of the reality of these particles. No one who studies the photographs and their method of production can have any doubt that we are dealing here with particles that have much the same properties as grains of sand; they are localized within a small space and obey apparently the laws of ordinary mechanics.

Parallel with this conviction, however, there developed another set of phenomena which throw doubt not so much upon the existence of the elementary particles as upon our whole mode of scientific thinking. The first discovery, the photoelectric effect, was made by Hallwachs about 1890. This was investigated qualitatively for a number of years; a theory was proposed by Einstein about 1906 and quantitatively established by Professor Millikan and others some years later. The phenomenon is simply described. When light is allowed to fall on a metal plate, it is found that negative electrons are shot out. Their specific charge can be easily measured and is found to be the same as for negative electrons from all other sources. But the most striking fact is that if the light is monochromatic, all of the electrons are emitted with the same speed and energy; the energy depends only upon the wave-length of the light, and not at all upon its intensity. This indicated that there is a certain atomicity about the interaction between radiation and matter—that radiation cannot be absorbed in any quantities whatever, but only in certain discrete amounts. These amounts are not fixed, however, but vary with the circumstances. The detailed study of this and many other phenomena has led to the recognition of the so-called *quantum of action.* I do not wish to go into the discussion of the quantum theory, but I merely mention the existence of this kind of an atom to make complete my tabulation of the fundamental atoms of physics.

For the first quarter of the present century physicists were occupied with the study of these three atoms—the negative electron, the proton, and the quantum of action. About 1925 Heisenberg collected all of the known information about them into the present form of the quantum theory. This theory describes satisfactorily almost all phenomena in which only these three particles are important, and for a time it seemed as if physics were almost finished, or at least was approaching a period of stagnation. This feeling lasted only a very short time, however, for things soon began to happen again. In 1930 Bothe and Becker, in the Reichsanstalt at Berlin, were shooting α-particles at targets made up of light elements. They found that when an α-particle struck a nucleus of beryllium, or one of a number of other elements, a radiation was emitted which seemed to have the character of γ-radiation. For a long time attempts had been made to find some way of doing something to an atomic nucleus, but most of them had failed. Here, however, was apparently a way of so shaking up a nucleus that it sent out γ-rays in much the way that an ordinary atom sends out light when it is struck by an ordinary negative electron. They investigated the nature of the radiation and found that it would pass through a fairly thick lead plate. Others immediately began to study the effect. By 1932 Irene Curie and M. F.

Joliot in Paris had found that although this radiation would pass through lead with comparative ease, it was stopped by a relatively small amount of paraffin, paper, or other substance which contained a large amount of hydrogen. Curie and Joliot recognized that the action of the paraffin was to provide a source for protons, and that in their experiments they were essentially measuring the transformation of the original radiation into protons. The interpretation of these experiments was first given by Chadwick, in the Cavendish Laboratory at Cambridge. He had for a long time played with the idea that there should be some neutral particles, and he saw in these experiments the confirmation of his expectations. Since then his interpretation has been well confirmed.

The situation is then something as follows. An α-particle strikes the nucleus of a beryllium atom and sticks to it. Since the resulting structure is unstable, it soon breaks up and shoots out an uncharged particle whose mass is close to that of a proton. Because this particle is uncharged, it produces no ions and cannot be detected in the ordinary way. But in time it is likely to hit another nucleus directly. This gives energy to the other nucleus, and its track can be seen in the Wilson chamber. The evidence for *neutrons* lies then in the sudden appearance of tracks in the middle of a Wilson chamber photograph without any apparent reason for them. The mass of the neutron can be deduced from the amount of energy and momentum which it gives to various nuclei. Since the proton has about the same mass as the neutron, protons are more readily affected than other particles. This explains the large effect of hydrogen in stopping neutrons and also in making them evident. The extreme penetrating power of neutrons can be seen from the fact that a proton whose speed is one-tenth that of light will go about one foot in air before it is stopped by collision with the molecules of air, whereas a neutron with the same speed may go for several miles before it makes a direct impact with a nitrogen or oxygen nucleus. For this reason neutrons are rather difficult to study; they tend to get away easily. Yet it has been possible to obtain photographs of the effects which they produce in the Wilson chamber. In addition to

FIG. 5. Tracks due to two parts of a nitrogen nucleus whose disintegration was produced by a neutron. [W. D. Harkins, D. M. Gans, and H. W. Newson, Phys. Rev. **44**, 529 (1933).]

producing simple recoils of nuclei, a neutron may actually break up a nucleus by sticking to it when it hits and, if this combination is unstable, the whole will break up and two parts will go off in different directions; these two parts can then be followed by means of the ions which they produce.

Fig. 5 shows the tracks of the two parts of a disintegrating nitrogen nucleus, as photographed by Professor Harkins at Chicago. One part is evidently much more massive than the other. In a process of this kind it is assumed that the ordinary laws of conservation of energy and of momentum are applicable so that both particles are moving in the direction of the original motion of the neutron. The energy of the two particles is made up of the kinetic energy of the original neutron and whatever energy may be obtained in the disintegration. By a study of a number of such photographs it is possible to determine the energy relations involved as well as to determine the mass of the neutron itself. It will be observed in Fig. 5 that the tracks appear in the middle of the Wilson chamber with no track leading up to them, thus indicating that the incident particle which causes the disintegration has no charge. One other possible explanation is that the disintegration is caused by γ-rays or x-rays, which also do not produce tracks, but a study of the momentum and energy relations shows that this is impossible, and that the cause must be a heavy particle. It is this kind of work that adds the neutron to our list of elementary atoms.

The next discovery in this line was made at the California Institute by C. D. Anderson, in September, 1932, and shortly thereafter in Cambridge by Blackett. The study of cosmic

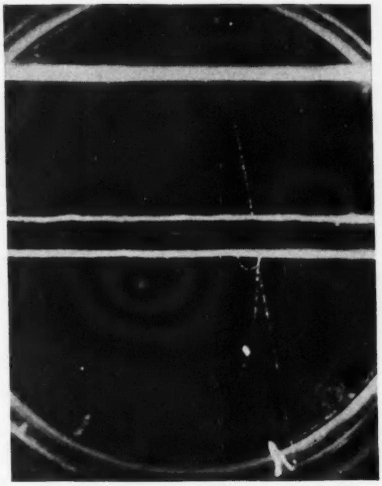

FIG. 6. Tracks due to cosmic-ray secondaries. [C. D. Anderson.]

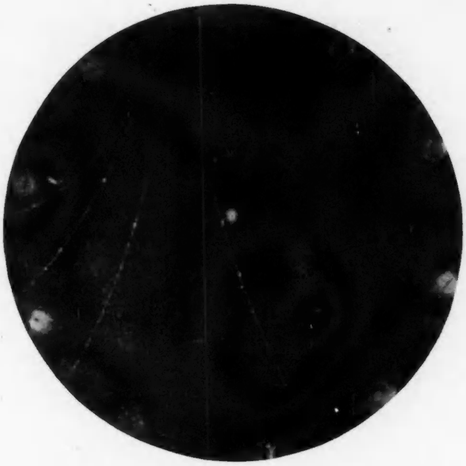

FIG. 7. Tracks due to positive and negative electrons produced by cosmic rays. [C. D. Anderson.]

radiation has engaged the attention of quite a number of physicists in the last ten or fifteen years, but there are still a good many disputed points as to their nature. All agree, however, that the immediate effect of the cosmic rays is the production of high speed electrons from matter that may be present. One method then of studying the radiation is to study the speeds and the behavior of these electrons. For this purpose Anderson built a Wilson chamber which, instead of being horizontal, was vertical. It was then expected that the electrons would pass through the chamber and would produce tracks. At first, of course, this was a very slow experiment, since all that one could do was to photograph the chamber and to hope that, at that particular time, an electron would be passing through. Out of some thousands of photographs a number were obtained which indicated electrons having very high speeds, for they went clear through the chamber, were deflected but little in passing near the molecules of gas, and produced rather thin tracks. This was not enough information for quantitative work, so Anderson placed his cloud chamber in the field of a strong magnet to deflect the electrons. This enabled him to estimate their energy with some accuracy if he assumed that the tracks were those due to ordinary negative electrons.

Fig. 6 shows one of the photographs obtained in this way. In the first place there is a straight track which goes clear through the cloud chamber and through the piece of lead placed in the middle of it. The electron was going too fast for the magnetic field to deflect it appreciably but in passing through the lead plate it came close enough to two negative electrons to knock them clear out of the lead. One leaves with an energy equal to that which it would have obtained in passing between two electrodes connected to a source of 30 million volts difference of potential. The other has an energy corresponding to about one million volts. The tremendous energy of the original particle can be imagined from the fact that it lost this 31 million volts of energy without being slowed down appreciably.

Fig. 7 shows a sight which is strange. There appear to be five tracks, all coming from the same point, and presumably produced at the same time. But although three of them bend to the left, as should negative electrons, the other two bend to the right, thus indicating positive charges. These positive charges cannot be protons or α-particles for if such particles were moving slowly enough to be bent by this amount in the magnetic field, they would produce tracks very much thicker than those produced by the electrons. It is necessary to conclude, then, that these tracks are due to a particle with a positive

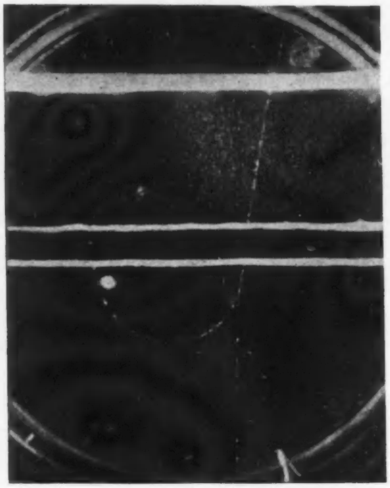

FIG. 8. Positive electron produces a negative secondary. [C. D. Anderson.]

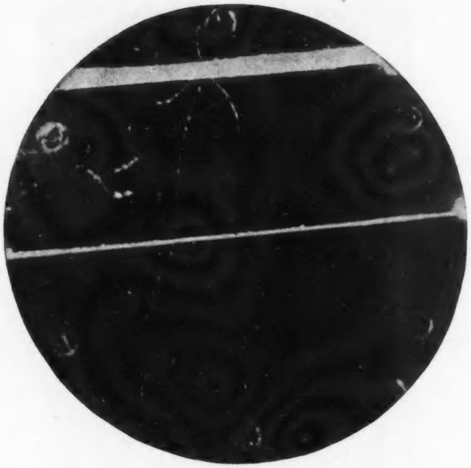

FIG. 9. Positive electron produced by γ-rays. [C. D. Anderson.]

charge, but with a mass something like that of the negative electron. Fig. 8 shows one of these positive charges, together with a secondary negative electron which it produced.

Having found this evidence for *positive electrons* and wishing to discover something more about how they are produced, Anderson placed a source of γ-rays near the edge of the chamber, and below it a thin sheet of lead. This was to see if the action of the γ-rays on the lead would produce any of these positive electrons. Fig. 9 shows one of the results. The rays impinge on the lead from above and a positive electron having an energy of 820,000 volts comes out from below. It crosses the chamber, passes through the aluminum sheet and, although it loses energy and is deflected in doing so, emerges with an energy of about 520,000 volts. This and similar photographs show that positive electrons can be produced by the action of γ-rays on matter. Fig. 10 shows a remarkable track of a positive electron produced by γ-rays which passed through the central thin lead plate three times and lost a little energy each time.

The discovery of the positive electron was not altogether unheralded by theoretical expectations. The relativistic quantum theory of the negative electron as developed by Dirac seemed to suggest that the requirements of relativity made necessary the existence of the positive electron. The correct interpretation of the theory in this respect was for some time obscure, but within the last year it has been developed by Oppenheimer to the point at which one believes that both the positive and the negative electrons must exist if one of them exists. There also appears to be a strong tendency for a positive electron and a negative electron to join with each other in which case their total charge

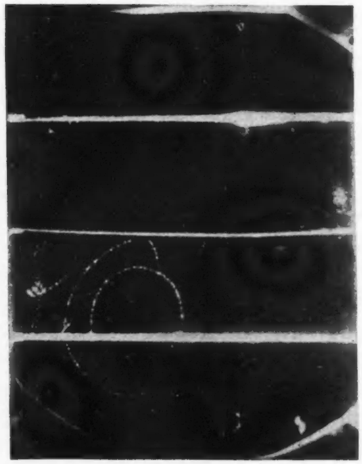

FIG. 10. Slow positive electron produced by γ-rays. [C. D. Anderson.]

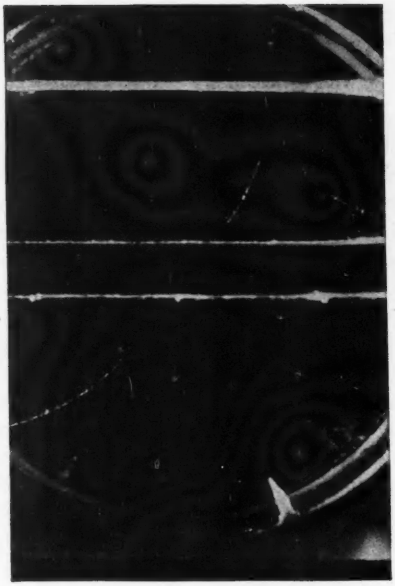

FIG. 11. A pair of positive and negative electrons produced by γ-rays. [C. D. Anderson.]

becomes zero and their mass is given off in the form of γ-rays. This explains the difficulty of observing the positive electrons; they do not live long. The reason that the negative electrons are easy to find is that there seem to be more of them available than there are positive electrons with which they can unite.

This tendency of a positive and a negative electron to unite, with the conversion of their mass into radiation, is paralleled by the possibility of the creation of a pair of positive and negative electrons out of a γ-ray. Thus, in Fig. 11, γ-rays come in from the top and a positive and a negative electron come out of the bottom of the lead.

The equivalence of mass and energy has been known since the development of Einstein's theory of relativity but in the present work we have it illustrated more clearly, perhaps, than anywhere else. A γ-ray, which is energy in the form of electromagnetic radiation, can be transformed into matter in the form of a positive and a negative electron, while matter in the form of a positive and a negative electron can disappear entirely with the formation of a certain amount

FIG. 12. The effect of a cosmic ray. [C. D. Anderson.]

of radiant energy. This type of transformation seems almost certain to be important in nuclear transformations.

Fig. 12 shows what may happen in a cloud chamber when a cosmic ray goes through it. It is very difficult to interpret a picture of this kind; it looks more like a burst of fireworks or a decorated Christmas tree than anything else. Clearly there are many positive and negative electrons produced, and probably also some γ-rays and neutrons. Whatever may be the products, it is certain that we know very little about the mechanism, and such pictures as these show that there is still a good deal to be learned about processes in which atomic nuclei are involved.

We have then in physics today at least five elementary atoms (Table I). First we have the quantum of action; its size can be accurately measured and the quantum theory has given a detailed way to take account of its behavior; yet

TABLE I. *The known atoms of physics (1933).*

Quantum of action	$h=6.54\times10^{-24}$ g·cm²·sec.$^{-1}$	
Negative electron	$-e=-4.770\times10^{-10}$ e.s.u.	$m=9.04\times10^{-28}$ g
Positive electron	$+e=+4.770\times10^{-10}$ e.s.u.	$m=9.04\times10^{-28}$ g
Proton	$+e=+4.770\times10^{-10}$ e.s.u.	$M=1.7\times10^{-24}$ g
Neutron	0	$M=1.7\times10^{-24}$ g

to say what it is, in any other sense, is beyond the ability of any one I know. Then we have the two electrons; they have equal masses and charges that are equal in magnitude but opposite in sign; they might be thought of as atoms of electricity. Then there is the proton; it has a charge equal to that of the positive electron and a mass some 1835 times as great. Finally, there is the neutron, with no charge and a mass approximately equal to that of the proton.

These five atoms are the elementary atoms of physics today, and are, I believe, atoms in a truer sense than any we have previously known. The Greek atom was an indivisible unit but this indivisibility was later somewhat obscured by those who wished to say that it was not indivisible but merely was not divided. I believe that at the present time the tendency is toward the original point of view and thus to regard an electron, for example, as an indivisible particle of electricity. At various times there has been a good deal of effort expended in investigating the structure of the electron and the forces which hold it together but no great amount of success has ever been attained, and the present view is that it is meaningless to talk about the structure of an electron. A true atom is really indivisible and structureless; there can be no possible way of dividing it because there is no instrument finer than it already is. The present problem of theoretical physics is to find the proper way of expressing this indivisibility in the equations which describe the behavior of the atoms.

TABLE II. *One possible system of elementary atoms of matter.*

Charge / Mass	$-e$	0	$+e$
m	Negative electron	(*Neutrino*)	Positive electron
M	(*Negative proton*)	Neutron	Proton

In much the same way in which Mendeleef established the periodic system of the chemical atoms, one wishes to establish some sort of a system of true atoms. One such system would be that shown in Table II. There are two possible masses, M and m, and three possible electric charges, $+e$, 0, $-e$. If a table of this kind is adopted there remain two empty spaces. There is a place for a light neutron, for which the name *neutrino* has been suggested; there is some slight evidence that it exists, although this is not as yet convincing. The other place is for the *negative proton;* if the proton itself is truly an elementary atom, the relativistic quantum theory almost requires the existence of a negative proton; there is no experimental evidence for it, however, and it will not be easy to find. I have put these names in parentheses in Table II in order to remind you that I have not said that these particles exist. They have not been shown to exist. It would make a nice symmetrical table if they did, but the desire for a certain symmetry is not scientific evidence.

TABLE III. *Another possible system of elementary atoms.*

Electricity	Positive electron
	Negative electron
Matter	Neutron

Proton = Neutron + Positive electron

There is still another possibility. It may be that aside from the quantum of action there are only three elementary atoms—the two atoms of electricity and the one atom of mass. This makes the proton itself a composite particle made up of a neutron and a positive electron. This is a very attractive system from many points of view. It would explain, for example, why there are some negative electrons loose; their corresponding positive electrons are fastened to neutrons. The decision between these and other possible systems cannot be made at the present time, but must be left for future experimental work and theoretical study.

I FEEL more vexed at impropriety in a scientific laboratory than in a church. The study of nature is intercourse with the Highest Mind.—LOUIS AGASSIZ

Where Do We Live? Reflections on Physical Units and the Universal Constants

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PHYSICISTS are always busy measuring things. Measurement implies methods of measurement and the adoption of arbitrary units in terms of which things are measured. Our arbitrary units have been chosen from a definitely practical standpoint and thus have no direct relation to the fundamental quantities of nature; that is, to the so-called universal constants, the quantities which are not properties of special substances but are fundamental characteristics of the physical world. Let us therefore have a look at the unit systems of physics.

First let me make some general remarks on the c.g.s. system. The discovery of the theory of dimensions of physical quantities was a truly great forward step in our science. I will not dwell on it long. By its means the units of all physical quantities are fixed in a natural way in a manner designed to give an especially simple form to certain physical equations. In this way to each physical quantity is assigned a dimensionality, and an absolute unit for it is fixed in terms of the arbitrarily chosen fundamental units of mass, length and time.

For example, let us consider the unit of temperature. (I purposely choose this example because for some strange reason the rational methods of the absolute unit system have not been applied to this quantity.) We choose some simple law of universal validity in which the new quantity, temperature, enters together with other quantities whose dimensions have already been fixed by the same procedure. We may take the Wien displacement law which says:

$$\lambda_{\mathrm{max}} T = \text{constant};$$

that is, that the wave-length of black-body radiation for which the spectral energy density is a maximum varies inversely as the temperature. This fixes the unit and dimensionality of temperature. Analogous to the textbook definition of the dyne or of the electrostatic unit of charge we have: *Unit temperature is that temperature for which the maximum spectral energy density of black-body radiation comes at a wave-length of one centimeter.* This fixes temperature as a quantity whose dimensions are L^{-1} and whose c.g.s. unit is cm^{-1}. Its numerical magnitude is also of convenient size, namely 0.288 degrees so that the ordinary (slightly chilly) room temperature of 15°C is just equal to 1000 cm^{-1} on this scale.

Besides illustrating the most striking case in which physicists have failed to apply their absolute method of constructing units, the example also illustrates a point which should be observed in applying the method. In Planck's radiation formula the combination $hc\sigma/kT$ occurs, where σ is the wave number of the radiation, T the absolute temperature and h, c and k are respectively, Planck's constant, the speed of light and the Boltzmann constant. We could define the unit of T in such a way that $hc\sigma/kT=1$ when $\sigma=1\ \mathrm{cm}^{-1}$; that is, unit temperature would be $hc/k\ \mathrm{cm}^{-1}$ or 1.4317 degrees which makes 15°C have a value close to 200 cm^{-1}. This definition of unit temperature is as good as the other from the dimensional standpoint. Their ratio is the transcendental number equal to about 4.965 and defined as the root of the transcendental equation,

$$(1-x/5)e^x=1,$$

which appears when one calculates the value of $hc\sigma/kT$ for which the Planck formula has a maximum spectral energy density on the wave-length scale. As there are a greater variety of calculations in which $hc\sigma/kT$ occurs than in which $\lambda_{\mathrm{max}} T$ occurs, it is advisable to choose the second unit of temperature rather than the first in building a convenient absolute system.[1]

[1] It is perhaps worth while to emphasize that there are two questions involved in the ordinary method of constructing derived units. One is that of the arbitrary choice of the fundamental law which shall serve as the basis for defining the derived unit. Thus unit force may be defined

The next point which I wish to make concerns the manner in which the arbitrary choice of basic units of mass, length and time is to be made.[2] The physicist wants to have a system such that quantities describing ordinary physical apparatus have convenient magnitudes. What dictates the choice of the size of "ordinary physical apparatus"? Clearly not so much fundamental physical considerations but considerations of a psycho-physiological nature. Ordinary apparatus is clearly apparatus which a human being manipulates readily. Its spatial dimensions are of the order of magnitude of the size of the human body; hence we have the meter and the yard and, in other metrological systems, units of this general size. The details of its construction are considerably smaller, about the size of the human hand, say; at least a lower limit is set by the scale of detail which the unaided human eye can readily perceive. This gives us the practical small units like the centimeter and the inch.

Similar remarks hold for mass and time. The order of magnitude of the practical unit of mass is determined by the amount of weight which one human conveniently manipulates, giving the kilogram and the pound. Smaller units like the gram get down toward the limit of sense discrimination in our unaided sense estimation of weight differences (estimation by "hefting" the weight held in the hand). This is more determined by the weight concept than the mass concept—but, as every physics teacher knows, these two concepts are not separated in the untrained mind and weight is generally regarded as the more direct one by beginning students. For time likewise our psycho-physiological structure suggests two orders of magnitude. One is the average waking interval during which the normal individual experiences a continuous stream of sense perceptions. This gives us the day. The other is the reaction time—the interval between receipt of a sensory stimulation and response to it. This gives us the second. The reaction time is clearly fundamental to physics, as limiting the experimentalist's ability to manipulate the apparatus with which he studies nature.

This, then, is where we live, in the sense in which the question is meant in the title of this paper. Our most direct experience concerns distances between the centimeter and the meter, masses between the gram and the kilogram and times between the second and the day. The order of magnitude of all these quantities is not so much a property of inorganic nature as it is of our psychological and physiological selves. As physicists we must seek more fundamental units in nature for dealing with our science and leave to the physiologist and psychologist the task of explaining why our life exists on the particular scale that it does.

This anthropomorphic element in our measuring systems is not to be deplored. It belongs there, for quantitative science is a unification by rational means of the quantitative aspects of our sense perceptions. Therefore a practical system of units should be such that our directly ob-

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as that force which gives unit mass unit acceleration, giving force the dimensions MLT^{-2}. Or we may define unit force as the force of gravitational attraction between unit masses at unit separation, which makes the dimensions of force be M^2L^{-2}. In the first case we have $F=ma$ without a universal constant, and have such a constant in $F=kmm'/r^2$. In the second case we have $F=mm'/r^2$ without a universal constant and then must write $F=kma$. I am trying to make the point that there is a fundamental entity here which can be made to appear in different aspects according to the particular arbitrary scheme selected. Likewise by using the Stefan law to define unit temperature we have unit temperature such that at unit temperature there is unit total energy of black-body radiation in unit volume. In this case the dimensions of temperature are not L^{-1} as in the text but $M^{\frac{1}{4}}L^{-\frac{1}{4}}T^{-\frac{1}{2}}$ owing to the fact that energy density varies as the fourth power of the absolute temperature.

The other arbitrary element is that which changes the choice of size of units without altering their physical dimensions. Examples: the two temperature units each of dimensions L^{-1} presented in the text; or the well-known case of the Heaviside-Lorentz electromagnetic units which are dimensionally the same as ordinary units but differ in regard to the way 4π appears in them.

For general discussions of dimensional theory see: Bridgman, *Dimensional Analysis*, Yale University Press, 1922; Wallot, *Handbuch der Physik*, Vol. 2, Chap. 1; Campbell, *Physics the Elements*, Cambridge, 1920, Chap. 14; Campbell, *Measurement and Calculation*, Longmans, 1928, Chap. 13; Lenzen, *The Nature of Physical Theory*, Wiley, 1931, Chap. 1; Bond, Phil. Mag. **9**, 842 (1930); Porter, *The Method of Dimensions*, Methuen, 1933; Stansfield, Nature **131**, 59 (1933).

[2] For interesting accounts of ancient and modern units see: Glazebrook, Proc. Phys. Soc. **43**, 412 (1931); Gliozzi, Atti di Torino **67**, 29 (1931).

served data come to us in convenient magnitudes. But, since we know that the trend of theoretical physics has been toward greater abstraction from direct observation, it is worth while to attempt such an examination of our metrology. Recognizing the human element involved in the choice of our practical units, we do not expect them to be especially adapted to the simplest description of the fundamental facts of nature.

Our physical theories attempt to relate all the facts of experience to a very few fundamentals. These fundamentals are universal in character and their measures are called universal constants. The natural thing for metrology is to define a system of units in terms of which the universal constants have convenient small values. I believe Planck was the first to devise such a system of units and G. N. Lewis has given them some attention. Lewis calls them "ultimate rational units."[3]

In setting about to build such a system the first thing which strikes us is that there are more universal constants than we need. Therefore we cannot set them all equal to preassigned numerical magnitudes. This is just another way of saying that there are in physics several dimensionless, pure numbers of a physical character. Let us set down one fundamental system of units and see how these pure numbers come in. In my experience, which is mostly in the field of atomic physics, the most convenient system is that of Hartree[4]:

Hartree's atomic units

Mass: μ, mass of the electron $\sim 9\times 10^{-28}$ gram

Length: a, radius of the first Bohr orbit in hydrogen $\sim 0.52\times 10^{-8}$ cm

Time: τ, time required for an electron to describe $(2\pi)^{-1}$ of a revolution in the first Bohr orbit in hydrogen $\sim 2.42\times 10^{-17}$ sec.

With these units many of the physical quantities of atom-theoretic interest have simple values. Thus, unit charge is $\mu^{\frac{1}{2}}a^{\frac{3}{2}}\tau^{-1}$ and is equal to the charge on the electron; unit angular momentum, $\mu a^2\tau^{-1}$, is equal to $h/2\pi$ in the usual notation, which is the angular momentum of the electron in the first Bohr orbit. All the derived units may be readily built up in this way. Some may object to the universality in that the length and time definitions refer to the particular substance hydrogen: to that I would reply that hydrogen is universal in being the prototype of all atoms, and so has a more general significance than it would have if it were just a particular element. In other words, when we are in possession of a complete atomic theory then it will be possible to phrase definitions of these units accurately in terms of any atom; hence they are universal.

The first of the pure numbers[5] presents itself as the magnitude of the speed of light in these units, $c=137a\tau^{-1}$. Another important one is the mass of the proton, $M=1840\mu$. Still another is the ratio of the force of electrostatic repulsion of two electrons to the force of gravitational attraction at any distance of separation. This is $e^2/k\mu^2$, where k is the gravitational constant; its value is 4.18×10^{42}. In the relativistic theory of cosmology there is another, the "radius of the universe," whose empirical value we do not know so well. This length is of the order of $10^{35}a$. Still another example, so simple as to almost elude our attention, is the ratio of the proton charge to that of the electron, -1.

There are others which are obviously combinations of these, such as the ratio of the gravitational force between two protons and their electrical repulsion which can evidently be expressed in terms of 1840 and 4.18×10^{42}. The existence of relations of this sort raises the obvious question whether the ones listed may not be related in some fundamental way as yet unrecognized. Thus we see that $1840\sim(40/3)\cdot 137$

[3] Planck, *Theory of Heat Radiation*, Blakiston, 1914, p. 173; Lewis and Adams, Phys. Rev. **3**, 92 (1914); Lewis, Phys. Rev. **18**, 121 (1921); Lewis, *Contributions from the Jefferson Physical Laboratory*, Cambridge, 1922, Vol. 15; L. L. Whyte, *Critique of Physics*, Norton, 1931.

[4] Hartree, Proc. Camb. Phil. Soc. **24**, 89 (1928). See also Ruark, Phys. Rev. **38**, 2240 (1931); Clark, Phil. Mag. **14**, 291 (1932). As to the experimental values of the constants the best critical survey is that of Birge, Rev. Mod. Phys. **1**, 1 (1929). See also Bond, Phil. Mag. **10**, 994 (1930); Birge, Phys. Rev. **40**, 228 (1932).

[5] Of course, the *magnitude* of any physical quantity in any system of units is a pure number, the ratio of the magnitude of that quantity to that of the arbitrarily chosen unit. But it is convenient to restrict the term somewhat to the case of the ratio of the magnitudes of two fundamental physical quantities. That is done here, although it must be admitted that the exact meaning of fundamental is not very precise.

but the discrepancy is outside the experimental error. Somehow $1840 \sim (4\pi^2/3)\cdot 137$ is more attractive but it does not fit quite as well! Similarly, $4.18\times 10^{42} \sim (137)^{20}$ has a stimulating effect on the imagination but unfortunately here also the discrepancy is somewhat larger than the experimental error. It is a pleasant arithmetical game to hunt for simple relations of this sort but it is hardly likely that this method alone will find the true relations if any such exist.[6] The problem of unifying these numbers in terms of more fundamental theory than any we possess at present is thus an open one at present.

Another attack on the problem raised by these numbers is that of attempting to give a theory which fixes the value of any one of them. Of course if we fix several of them by a unified theory we have also determined relations between them. Eddington[7] has made the most definite attempts of this sort that I know. It is obviously out of place to discuss the details of his interesting hypotheses here.

There is a practical sense in which these numbers are of importance as they give us the means of passing from the particular Hartree system of units to all others which may with equal right be called fundamental. The great range of the numerical magnitudes occurring in physical theory makes it necessary to extend our unit system to include multiples and submultiples of the basic units of each kind. This is clearly recognized in the metric system where auxiliary units are provided by multiplying the basic units by powers of ten. Even this ten has an anthropomorphic origin, for it is the base of our system of numeration which is related to our possession of ten fingers. The powers of 137 give us a set of very convenient multiples for extending the Hartree system over the field of atomic problems. Thus with regard to length we have

- $137a$: $(4\pi)^{-1}$ times the wave-length of the limit of the Lyman series in hydrogen
- a: Radius of the first Bohr orbit
- $a/137$: $(2\pi)^{-1}$ times the amount of the shift in wave-length of radiation scattered through $\pi/2$ in the Compton effect
- $a/137^2$: Electromagnetic radius of the electron.

For energy the quantities of interest in atomic physics proceed according to the even powers of 137:

- $137^2\mu a^2\tau^{-2}$: Relativistic energy equivalent of the rest-mass of the electron
- $\mu a^2\tau^{-2}$: Twice the ionization energy of the hydrogen atom
- $137^{-2}\mu a^2\tau^{-2}$: A quantity of the order of the relativistic fine structure of the hydrogen spectrum and of the energy due to magnetic interaction of spin and orbital angular momentum in hydrogen
- $137^{-4}\mu a^2\tau^{-2}$: A quantity of the order of magnitude of the natural breadth of ordinary spectral lines on the energy scale.

These four units of energy are adapted for convenient discussion respectively of (1) energies involved in radioactive transformations of an atom, packing energies, and problems in nuclear physics generally, (2) the main energy terms in atomic spectra, (3) the more detailed energy terms in the structure of atomic spectra and (4) the limit on the applicability of Bohr's rule connecting the frequency of light emitted during a quantum jump with the difference in energy of the two states involved. Similar tables may be made for other quantities although for them the range of powers of 137 is not usually so great.

It is of some interest to note that the quantity 137 is the ratio of transformation from electrostatic Hartree units to electromagnetic Hartree units. This brings clearly to the fore the real reason why all magnetic susceptibilities (except for ferromagnetics) are very much smaller than the corresponding electric susceptibility. If we apply an electric field to an atom, the induced dipole moment P is given by $P=\alpha E$ where E is the applied field and α is the atomic polarizability. It has the dimensions of a volume and for all atoms is of the order of a^3. Correspondingly, if we apply a magnetic field to the atom, we get an induced magnetic moment that is proportional to the magnetic field. The coefficient of proportionality may be called the magnetic polarizability and in electromagnetic units it also has the dimensions of a volume. But it is always much smaller than a^3. This is because of the difference in the

[6] A number of relations of this type have been published recently: Witmer, Nature **124**, 180 (1929); Phys. Rev. **42**, 316 (1932); Perles, Naturwiss. **16**, 1094 (1928); Clark, Naturwiss. **21**, 182 (1932); Rojansky, Nature **123**, 911 (1929); Mills, Science **75**, 243 (1932) and criticism by Birge, p. 383.

[7] Eddington, Nature **124**, 840 (1929); Proc. Camb. Phil. Soc. **27**, 15 (1931); Proc. Roy. Soc. **A126**, 696 (1930); Fürth, Zeits. f. Physik **57**, 429 (1929); Bond, Proc. Phys. Soc. **44**, 374 (1932); Flint, Proc. Phys. Soc. **42**, 239 (1930); Beck, Helv. Phys. Acta **6**, 309 (1933); Schames, Zeits. f. Physik **81**, 270 (1933); Narlikar, Nature **131**, 134 (1933).

mechanism involved. In the electric case, electric forces act on electric charges to displace them and cause an electric moment. In the magnetic case, however, the magnetic field has to induce an electric current, which is small owing to the factor $(1/c)$ in the Maxwell equation for electromagnetic induction, and this in turn has to produce a magnetic moment which is smaller still by the factor $(1/c)$ occurring in the Maxwell equation for Ampere's law. Thus we expect diamagnetic susceptibilities to be of the order of $(137)^{-2}$ times the corresponding electric susceptibilities. This is in fact the case. The same is true for the permanent moments of molecules. The permanent electric moments of molecules, as measured from temperature variation of the dielectric constant, are all conveniently measured in terms of the Hartree unit, ea. Now ea is of the correct dimensions to measure magnetic moment on the electromagnetic system, but the actual convenient unit is the Bohr magneton which is $ea/2.137$, or twice 137 times smaller.[8] This again comes from the fact that electric moments are produced directly by the charges while magnetic moments arise from motions of charges whose speeds relative to the fundamental speed of electromagnetic theory are of the order $1/137$. While we live on a scale of space and time for which the speed of light is enormous and relativistic effects remote, the magnitude domain of atoms sees the speed of light as a smaller magnitude relative to its own speeds of common occurrence.

So much for the extensions of the Hartree units by powers of 137. These are obviously the extensions needed when dealing with electrons and their relation to the electromagnetic field as modified by the existence of Planck's quantum of action. If we are interested in molecular problems, extensions by powers of the quantity 1840 obviously are of interest. For example, the frequency ν of vibration of a harmonic oscillator is given by

$$\nu=(2\pi)^{-1}(k/m)^{\frac{1}{2}},$$

and so the radiation wave number corresponding to this is

$$\sigma=(2\pi c)^{-1}(k/m)^{\frac{1}{2}}.$$

For a molecule the binding forces are principally electrostatic in character so we may expect k, which has the dimensions of force per unit length, to be of the order $\mu\tau^{-2}$. The moving masses in a molecule are nuclear in magnitude and so are of the order 1840μ. Also $c=137a\tau^{-1}$. Thus it appears that our natural unit for molecular vibration frequencies is

$$\sigma=(2\pi\cdot 137)^{-1}(1840)^{-\frac{1}{2}}a^{-1}\sim 5100\ \mathrm{cm}^{-1}.$$

In point of fact this is a very convenient unit for the purpose. The vibrational energy levels of H_2 in the normal electronic state have a spacing of 4260 cm^{-1}. For heavier molecules the frequency is lower, partly because their masses are large compared to the proton mass (a factor of the order $100^{-\frac{1}{2}}$ is easily introduced in this way) and partly because the electrostatic forces are weaker when the electron orbits are considerably larger than a as in the heavier molecules. Similarly for the rotational energy of molecules. The rotational energy states are characterized by the molecule's possessing an integral number of units of angular momentum. The energy is $p^2/2I$ where p is the angular momentum and I is the moment of inertia. Since the equilibrium position of the nuclei is determined by a quantum-dynamical treatment of the electrostatic forces, the length factor in I is of the order a but the mass factor is of the order 1840μ. Hence for $p=1\hbar$ the natural unit of rotational energy becomes[9]

$$\hbar^2/(1840\mu a^2)=(1/1840)\mu a^2\tau^{-2},$$

or $2/1840$ of the ionization energy of hydrogen. The wave-number equivalent of this is 119 cm^{-1} which is of convenient size for the purpose in hydrogen although for other molecules the rotational energy is a small fraction of this unit rather than a multiple because generally the nuclear mass is greater than 1840μ and the internuclear distance is greater than a.

A simpler example is that of density. Since the volumes of atoms are determined by their electronic structures they are of the order a^3. The mass is principally nuclear so the natural unit of density is not μa^{-3} but $1840\mu a^{-3}$. This is about 11.3 $\mathrm{gram}\cdot\mathrm{cm}^{-3}$, rather larger than most densities of solids or liquids because the molecular volumes are more than a^3 by somewhat more than the molecular weights exceed 1840μ. But the main point is that this is a natural unit in order of magnitude and is obviously close to all

[8] Since it is the square of the permanent moment which occurs in the temperature-dependent part of the susceptibility in the Langevin-Debye formula the relative magnitude of the polarizability and the permanent moment terms in the susceptibility is the same in the magnetic as in the electric case. See Van Vleck, *The Theory of Electric and Magnetic Susceptibilities*, Oxford, 1932.

[9] $\hbar=h/2\pi$.

solid densities. It is of interest to note that here we have a case where our natural unit agrees in order of magnitude with the practical c.g.s. unit. That is because density is an intensive property of matter and so is the same for matter in bulk as for single atoms.

Let us next consider temperature from the standpoint of natural units. The natural unit following the method introduced at the beginning of this paper is a^{-1} or 1.89×10^{8} cm^{-1} which is 286 million centigrade degrees. This is clearly not a convenient unit for discussing our direct perceptual experience. But it is the natural unit for discussing temperatures in stellar interiors because at unit temperature on this scale we have the temperature so high that the quanta of most common occurrence are those which have energies comparable with the ionization energies of atoms; there is almost complete ionization there.

To find a derived unit more appropriate for dealing with the temperatures of our common experience, we must single out the most important fundamental characteristic of such temperatures. It is that they are such that ordinary molecules in thermal equilibrium are distributed over a small number of rotational states. This suggests the use of 119 cm^{-1}, the natural unit of rotational energy on the wave-number scale as the unit of temperature. This is 170 degrees which makes room temperature (300 degrees) have the value 1.76 and shows that we have adopted a unit of convenient size by this method.

The argument which led us to this unit is not completely fundamental because it did not present the fundamental reason why it is that temperatures of common experience have the property that molecules are distributed over a small number of rotational states. The fundamental reasons for this are of two characters. One is biochemical and is connected with the fact that the biochemical equilibria fundamental to our existence require temperatures of this order. The other is cosmological and is connected partly with the fundamental reason why stars have the intrinsic luminosity which they do have (an atomic phenomenon because it is the scattering of radiation by matter which limits the flow of radiation out from the stellar interior), and partly with the fundamental reason why the radius of the earth's orbit is what it is (this is the problem of the dynamical theory of the genesis of the solar system which when completely solved will presumably relate the question to several pure numbers, such as the total number of particles in the universe, and perhaps the cosmological radius of the universe or the mean density of matter in our galaxy expressed in atomic units, and the ratio of gravitational forces to electrical forces). Such fundamental considerations determine the temperature of the earth's surface. Their coincidence with the biochemical criteria will afford part of the fundamental physical theory of the fitness of the earth as an abode for life.

This completes our survey of the Hartree units and their extension to other natural units of physical interest by means of the quantities 137 and 1840. Many other applications of the same kind suggest themselves, such as the natural unit of heat capacity or specific heat, but enough has been said to show how the method provides convenient natural units in every case in which the fundamental physics of the situation involved is clearly understood.

These systems obviously do not provide us with convenient units for astronomical purposes. These are provided by moving off from the atomic units with appropriate use of the pure number 4.18×10^{42} which takes us from the part of physics where electrodynamic effects predominate to that part in which gravitational effects are important. I will not attempt to do this in detail as it would take us rather more deeply into cosmological theories than is appropriate here. I merely mention as an example that, since we know the size of stars to be due to a balance of gravitational pressure and radiation pressure when matter exists at temperatures of the order of one unit on the atomic energy scale, this balance fixes a natural unit for stellar diameters which is of convenient size.[10] To fix a natural unit in this way for the size and mass of the earth would require a definite view of the mechanics of the formation of the solar system. Since we know how to fix the natural unit of stellar sizes and if we accept a tidal fission theory of the genesis of the solar system,[11] I think it is clear that we may in this way construct natural units for the sizes involved in the solar system. Our knowledge is rather too incomplete at present to do this in explicit form. Hence, provisionally, we need to make an *ad hoc* introduction of the earth's radius in terms of

[10] Eddington, *The Internal Constitution of the Stars*, Cambridge, 1926, Chap. 1.

[11] Jeans, *Astronomy and Cosmogony*, Cambridge, 1928, Chap. 16.

atomic units as a stepping stone from these units to some of the familiar phenomena of terrestrial experience. This radius is $R=1.21\times 10^{17}a$.

With this unit and our natural unit of density we find that the obvious natural unit of mass for the whole earth is

$$1840\mu a^{-3}\cdot(4/3)\pi R^3=12.6\times 10^{27}\text{ grams.}$$

This is, of course, of the right magnitude, the actual value being 0.485 of this unit owing to the earth's mean density being about half our natural unit of density. To get back to the first thing in the freshman physics course, let us next consider the natural unit of acceleration of gravity. It is evidently the acceleration produced at a distance R by a body of mass equal to our unit terrestrial mass. This is 2010 $\text{cm}\cdot\text{sec.}^{-2}$ and of course bears the same ratio to the value 980 as does our mass unit to the mass of the earth. In the same way the obvious terrestrial unit of time is, analogous to the atomic unit, the time in which a body describing a circular orbit of unit radius about an earth of unit mass describes one radian of its path. This is about 5700 sec., a little over an hour and a half.

I will not go on with the further development of explicit units appropriate for terrestrial and astronomic uses. My object was simply to illustrate the method. Those who are familiar with the work of G. N. Lewis on "ultimate rational units" will recognize that there is a considerable similarity between what he did and the subject of this paper. The program here is much more modest, however. Nothing more is attempted than to show how the universal constants determine not one system of fundamental units but a family of systems fully adapted for convenient numerical discussion of the different parts of physics. "Convenient" is meant in the sense that the units are such that the numerical magnitudes actually occurring in nature are in each case of the order of unity so that there are no large powers of ten to be handled in the calculations. The ordinary practical c.g.s. system was exhibited as occupying a place among these families that is conditioned by the physical nature of human beings themselves.

Lewis' program was more ambitious in that he hoped to discover the actual numerical magnitude of new physical quantities through use of the postulate that such magnitudes would be "simple" numbers. The weakness of the postulate lies in its indefiniteness as to the meaning of a simple number. I use the same notion here in a less restricted form by supposing that in the appropriate fundamental units all physical quantities have numerical magnitudes of the order of unity. If one restricts simple numbers to mean numbers of the form $2^a3^b5^c7^d\pi^e$, where a, b, c, d, e are themselves positive or negative numbers of magnitude less than 10 or rational fractions whose numerator and denominator are each less than 10, the field of simple numbers while finite still includes quite a variety of numbers and this method leaves us with no rational way of choosing which simple number applies in a particular case. Moreover there are cases in which this field is too restricted as, for example, the appearance of the transcendental number x, satisfying $(1-x/5)e^x=1$ in the Wien displacement law.

That the numbers occurring are of the order of unity in the appropriate fundamental units seems however to be quite generally true. This much weaker principle is generally attributed to Einstein.[12] He remarked that purely mathematical processes used in physics never produce large numerical coefficients. This is a purely empirical observation for which no reason is given. It is nevertheless an important supplement to the ordinary argument from dimensions. For example, we all know the classic example of dimensional analysis which gives the result that the period of swing of a pendulum is proportional to $(l/g)^{\frac{1}{2}}$ where l is its length and g the acceleration of gravity. The pure number factor of proportionality is not given by dimensional analysis. Yet the principle used here makes us confident that that factor will not be some great thing like 10^{10} or anything small like 10^{-10}. It is actually 2π which is, in this case, not only of the order of unity, but simple according to the above definition of simple.

I conclude these reflections with the hope that they may serve to clarify the relation of the unit systems of physics to the fundamental entities of physics. I am sure that adoption of fundamental units along the lines here indicated can do much to simplify the calculations involved in all branches of physics and to bring out the nature of the fundamental interrelationships of the subject.

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[12] Einstein's only publication on this subject occurs in Ann. d. Physik **35**, 687 (1911). He gives the pendulum example and obtains $T=C(l/g)^{\frac{1}{2}}$ as usual and says: "One can, as is known, get a little more out of dimensional considerations, but not with complete rigor. The dimensionless numerical factors (like C here), whose magnitude is only given by a more or less detailed mathematical theory, are usually of the order of unity. We cannot require this rigorously for why shouldn't a numerical factor like $(12\pi)^3$ appear in a mathematical-physical deduction? But without doubt such cases are rarities. . . ."

The New Physics Laboratory at the University of Texas

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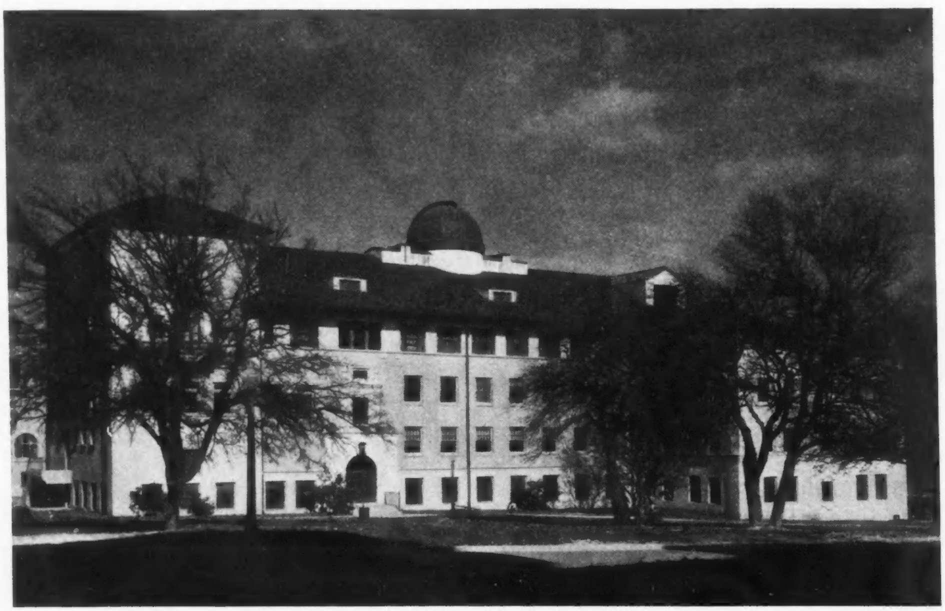
THE recent building program at the University of Texas included a new physics laboratory which has just been completed at a cost of a little more than half a million dollars. This building is a five-story structure exclusive of a students' astronomical observatory and a basement that is completely underground. The building is L-shaped with a longer section of 66×200 ft. and a shorter section of 60×40 ft. The construction is a reinforced concrete frame with hollow tile walls and an outside facing of buff gray mixed brick trimmed with Cordova limestone. The type of architecture is modernized Spanish Romanesque with a red tile roof topped by the observatory dome.

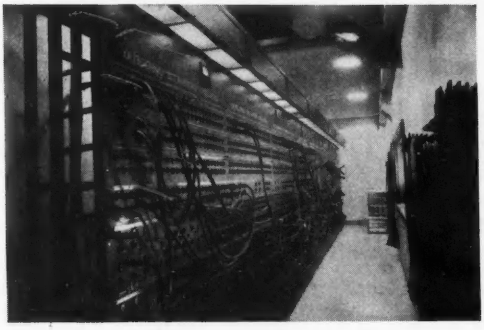
There are 60,000 ft.^{2} of floor space, not including the corridors. This space is divided into 5 large first and second year laboratories, 2 lecture rooms, 2 apparatus rooms, 2 shops, 3 storerooms, 4 class rooms, a departmental library, a staff room, 1 laboratory each for heat, mechanics, seismology, radioactivity, gratings, x-rays, crystal structure, electrical standards, electrical measurements, vacuum tubes, electric waves, high frequency currents, optics, photometry, and photography, 23 dark rooms, 19 offices, 21 research rooms, a constant temperature room, an observatory with an 18-ft. dome, a transit room and a meridian circle room. There is a storage battery room with batteries capable of furnishing 75 amperes at 400 volts, 100 amperes at 34 volts, 600 amperes at 44 volts; a generator room with four motor generator sets; a switchboard room with a 1250-terminal board; a central radio room; and a clock room with time signal equipment and a crystal-controlled constant frequency generator.

The heating and ventilating system, which is



General view of the building.

thermostatically controlled, furnishes either cool air, or air heated by steam coils, as the temperature requires. The ceilings and walls of all the larger rooms and corridors are treated with sound absorbing material. The floors are either



The switchboard.

oak or asphalt tile on concrete except in the basement where the floor surface is dust-proof concrete. The machines in the shops have individual motors and all the heavier lathes, grinders, milling machines and shapers are mounted on vibration-absorbing bases. There is an automatic elevator service from the basement to the fourth floor.

The basement is devoted largely to seismology, spectroscopy, crystal growing, constant temperature work and includes 10 research rooms. The shops, x-ray and crystal structure laboratories, heat and mechanics laboratories, storage batteries, motor generator sets and switchboard are on the first floor. The lecture rooms, electrical

The shop.

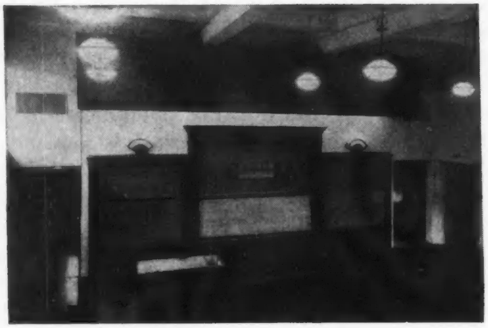
measurements, vacuum tube and electric wave laboratories are on the second floor. The third floor is used almost entirely for elementary laboratory work. A large central apparatus supply room for the first and second year laboratories and three class rooms are also on this floor. The library, the optics and photographic laboratories, the staff room, a class room and several offices are on the fourth floor. Eighteen dark rooms, a chemical and photographic supply store room, a photometer room and the entrance to the students' astronomical observatory are on the fifth floor.

One of the two lecture rooms has a seating capacity of two hundred and fifty, the other of one hundred and forty. These lecture rooms and a common preparation room are equipped with triplicate electrical supply panels and outlets for water, gas, high pressure compressed air and low pressure compressed air, so that demonstration experiments may be set up in the preparation room and readily transferred to either lecture room on tables with wheels or castors. Both lecture rooms are equipped with projection lanterns, reflecting galvanometers, large-scale voltmeters and ammeters, and loudspeakers.

The library.

The elementary laboratories and the central apparatus storeroom are designed to care for a large number of laboratory sections with twelve pairs of students in a section for two-hour periods and all the students in a section performing the same experiment. Each elementary laboratory is 42×26 ft. and is furnished with twelve wooden tables arranged around the walls and twenty-four steel stools. The tables are

supplied with gas and compressed air, and with electricity from a uniform supply panel with two battery circuits, 110-volts d.c. and 110-volts a.c. The 110-volt circuits are connected through dual over-load circuit breakers. In the middle of the



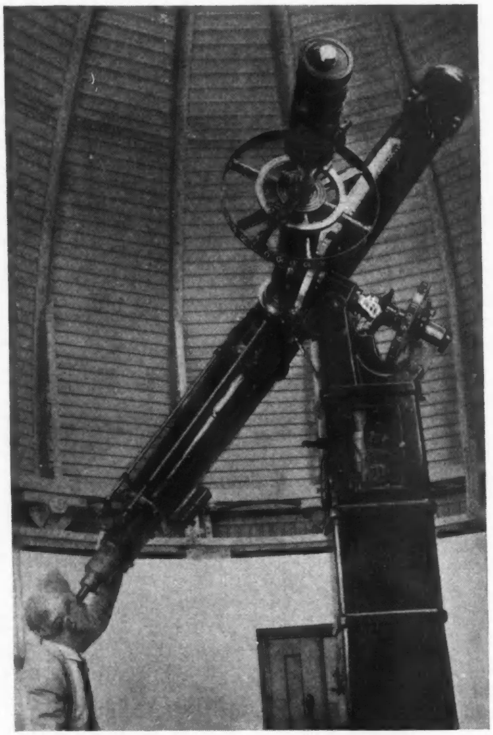
The larger lecture room.

room there is a large central table with transite top which is equipped with supply panels, gas, compressed air, water and a sink at each end. There are storage cabinets under this table with doors and drawers on each side of it.

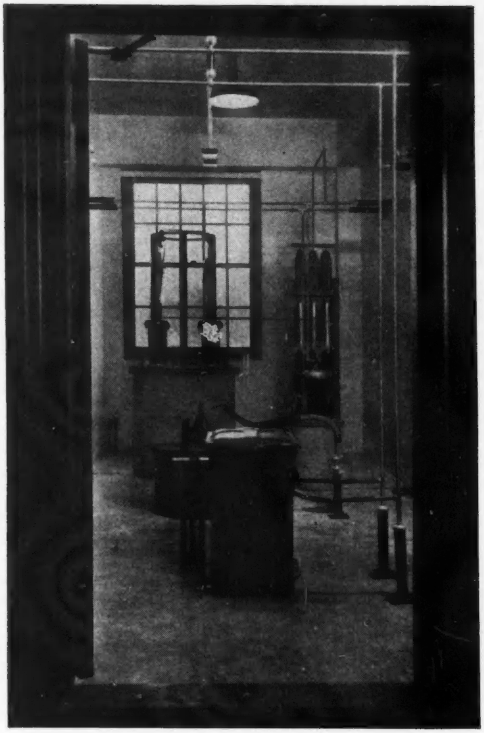
The advanced laboratories are especially equipped for seismology, electrical measurements, vacuum tubes and electric waves, x-rays, optics and astrophysics. Piers are provided for mounting vertical and horizontal seismographs, sound proof booths are provided for certain electrical experiments, and the laboratories for electrical measurements, vacuum tubes, high frequency currents and electric waves are completely lined with copper screen. The x-ray and crystal structure laboratories are equipped with a 100,000-volt supply that is capable of furnishing 100 milliamperes of direct current continuously. There are other transformers that will furnish 30,000 and 13,000 volts. The observatory has a 9-in. refracting telescope, astro-cameras, chronometers and a 3-in. transit. There is also a flat roof deck over the shorter section of the L at the fourth floor level where optical and astronomical observations can be made from twelve rigid piers around the edge of this open deck.

Each research room is approximately 26×12 ft. and is furnished with three tables with heavy wooden tops on metal supports made of gas-pipe fittings. Each research room is furnished with gas, compressed air and water. There are two or three of the uniform electric panels in each room and about half of the rooms have a concrete pier with a soap-stone top in the middle of the room.

A special feature of the building is the installation of apparatus strips on the walls of laboratories and research rooms. These metal strips are bolted into the walls and made flush with the plaster, and permit apparatus or shelves to be fastened to the walls at nearly any place and at any desired elevation. There are also 1.5-in. thimbles through the walls to adjacent rooms and corridors so that temporary connections between rooms may be made without cutting through a wall. Larger thimbles through the walls are in line for the entire length of the building on each floor, others for the entire width on each floor, and still others for the entire height



The telescope.



X-ray transformer.

of the building. This makes it possible to get straight-line connections for the entire length, entire width or entire height on any floor and in nearly every room. The switchboard is especially complete and affords possibilities of connecting batteries, direct-current supply up to 500 volts, alternating-current supply up to 300 cycles per second and a constant frequency of 10^3, 10^4 and 10^5 cycles per second to a uniform type of connecting panel in all rooms. In addition to the motor generator sets, which includes one set that will furnish 1200 amperes, there are rectifiers for charging low-capacity storage batteries. All laboratories, shops, storerooms, offices and corridors are connected by a system of forty-three high quality intercommunicating telephones. A 1000-cycle tone from speakers is used to call any one of the staff at any place in the building by a code signal. Another special feature is the built-in display cabinets in the corridors; the displays include a Foucault pendulum, an earthquake recording seismograph, a vibration indicator, a voice wave-form oscillograph, and a rotating magnetic field demonstration.

There are about one thousand students registered in the courses of the department and these students are classified approximately as follows: 700 first year, 150 second year, 100 third year, 25 fourth year and 25 graduate students. The staff of the department consists of 4 full professors, 2 adjunct professors, 2 instructors, 7 tutors, 18 assistants, 4 mechanicians and laboratory aides and 1 stenographer-librarian.

The representative of the department on the building committee was Dr. C. P. Boner and the department is indebted to him for the careful supervision of the plans and construction that resulted in a building that is excellently adapted to its purpose.

A GREAT advance in science, though nothing could at first sight seem less poetical, inevitably results in a change both in the style and in the substance of poetry, as well as in the taste that judges it. A whole book might be written on the influence of Copernicus on poetic production, and another on poetry as modified by Darwin. *In Memoriam*, for instance, though written before the *Origin of Species*, is full of the thoughts which were soon to be clarified by that work, and could never have been written had not the *Vestiges of Creation* appeared shortly before: while, though Milton still hankered after the Ptolemaic cosmogony, *Paradise Lost* is in part the work of Galileo and Kepler. It is hard—if we may leap to a later date—to imagine the loss the literature of Germany and the world would have sustained if Goethe had not been a student of science. Faust is informed throughout by the new scientific spirit, alike in its doubts and in its certainties; the philosopher is the physicist of the early nineteenth century, and Mephistopheles is the darker aspect of the same philosophy.—E. E. KELLETT, *The Whirligig of Taste.*

APPARATUS, DEMONSTRATIONS AND LABORATORY METHODS

Flame Temperature Measurements by the Line Reversal Method for Second Year Laboratory Students

GEORGE W. SHERMAN, JR., *Department of Physics, Purdue University*

MOST laboratory experiments for measuring flame temperatures fail because of difficult technique or because of lack of knowledge of the laws of chemical reaction in the flame. The method of measurement by various sizes of thermocouples is not only tedious, but very inaccurate. The gauze method is also long and difficult because of radiation corrections. The method of calculating flame temperature by chemical reaction[1] is not only very difficult and requires a considerable knowledge of chemical reactions in the flame, but also depends upon the knowledge of the specific heat of gases at high temperature; these specific heats are not well determined at the higher temperatures and therefore introduce considerable error in the calculated values of flame temperature.

The author has used the line reversal method with students in a second year laboratory course with considerable success.

Following the method of Kurlbaum[2] which was later further developed by Fery,[3] by Henning and Tingwaldt[4] and also by the United States Bureau of Mines,[5, 6] a simple apparatus was devised as shown in Fig. 1. A standard 6–8 volt automobile headlight bulb, B, is lighted from a toy transformer, T, the current being controlled by the rheostat R_1. The lens L_1, a telescope objective of 2 in. diameter, forms an image of the filament in the section of the flame to be studied. A similar lens, L_2, throws an image of the former image and also of the flame upon the slit of a small pocket spectroscope, *P.S.*, by reflection from the mirror M. The exit pupil of this spectroscope is provided with a small piece of Corning Red Glass to absorb all but the red end of the spectrum.

The flame is properly adjusted and colored with lithium chloride. The line 6708A is seen in the spectrum superimposed on the red band from the light bulb. The rheostat R_1 is now adjusted until the continuous spectrum is so bright that the lithium line is on the point of reversal. The mirror M is then removed so that the image falls on the filament, t, of a calibrated disappearing-filament pyrometer bulb. Viewing through the red glass, G_1, and the ocular, O, R_2 is adjusted for a brightness balance, and the temperature thereby measured.

Measurements of the temperatures in several parts of the flame may be made by the students in one hour with an accuracy far exceeding that of any other method yet tried. The general principles included in a first course in physics, supplemented with a small amount of information regarding resonance spectra[7] and the laws of radiation, prepare the student for the measurements.

The brightness to which the lamp filament may be run limits this method to about 1800°C. By using the crater of a carbon arc with an excess current, the author and H. H. Lurie[8] determined temperatures to 3000°K for welding torches.

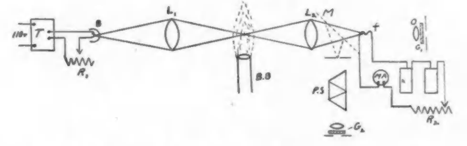


FIG. 1. Apparatus for measuring flame temperatures.

[1] G. A. Goodenough and G. F. Felbeck, University of Illinois Eng. Exp. Sta. Bull. 139 (1924).
[2] F. Kurlbaum, Zeits. f. Physik **3**, 187, 332 (1902).
[3] C. Fery, Comptes Rendus **137**, 909 (1903).
[4] F. Henning and C. Tingwaldt, Zeits. f. Physik **48**, 805 (1928).
[5] G. W. Jones, B. Lewis, J. B. Friaup and G. St. J. Perrott, J. Am. Chem. Soc. **53**, 869 (1931).
[6] B. Loomis and G. St. J. Perrott, Ind. and Eng. Chem. **20**, 1004 (1928).
[7] See, for example, G. E. M. Jauncey, *Modern Physics*, p. 328.
[8] H. H. Lurie and G. W. Sherman, Ind. and Eng. Chem. **25**, 404 (1933).

An Electrostatic Voltmeter

MILTON Y. WARNER, *Fayerweather Laboratory of Physics, Amherst College*

IN the demonstration of experiments on static electricity it is often very desirable to show the potential of a static charge or the difference in potential between the poles of a static machine. These potentials often run up to values far beyond the range of the instruments usually available for measuring such quantities. In order to be able to demonstrate them quantitatively to a large class, the instrument described in this paper was built and permanently placed on one wall of the lecture room with a calibrated scale on the opposite wall. The instrument is of the repulsion type and is therefore useful in measuring both a.c. and d.c. potentials. Thanks are due Professor Bergen Davis,[1] of Columbia University, for drawing the designs.

In Fig. 1 is shown a cross section of the voltmeter.[2] It is essentially a Coulomb's balance in design. Two hollow, copper balls, B_1 and B_2, in the same horizontal plane and 15 cm apart, are hung on a frame which is supported by a steel wire suspension so as to permit rotation about a vertical axis bisecting their line of centers. Two similar copper balls, B_1' and B_2', are mounted rigidly in the same horizontal plane as the movable balls. The fixed balls are attached to the head of the instrument by hollow brass tubes and so mounted as not to interfere with the motion of the movable balls until the balls strike each other. In the uncharged condition, each of the movable balls is barely in contact with one of the fixed balls. This position may be determined from the position of the spot of light reflected from the mirror attached to the moving system. The four copper balls have an external diameter of 5 cm. They are inclosed in a cylindrical copper shield S, 61 cm in diameter and 46 cm in height. The ends of this cylinder are wooden disks. The upper end has a circular opening in which rests the main part of the instrument, attached to a Bakelite disk K. Thus the working parts of the voltmeter may be lifted out as a complete unit and without disturbing the field.

To prevent leakage care was taken to have all surfaces which would be exposed to the electrostatic field, as smooth and as of large radii of curvature as possible. The dash-pot blades are an exception in this respect but, as they are totally immersed in oil which is contained in a glass dish resting on an insulating support, it was assumed that no serious leakage would result from this source. Subsequent experience confirmed this view. In the original plans Professor Davis used a sphere filled with oil for damping the oscillations. This was tried but it was found that, for the erratic potentials for which this instrument is to be used, the vanes V swinging in oil are much more effective.

The movable balls are attached to a light brass tube. At right angles to this horizontal tube is soldered a piece of 3.2-mm brass rod. The damping vanes are attached to the lower end of this vertical rod and at the upper end there is a clamp for gripping the lower end of a piece of No. 10 steel piano wire. The upper part of the vertical rod carries a mirror M which reflects the light from an incandescent filament to the scale on the wall of the room. For holding

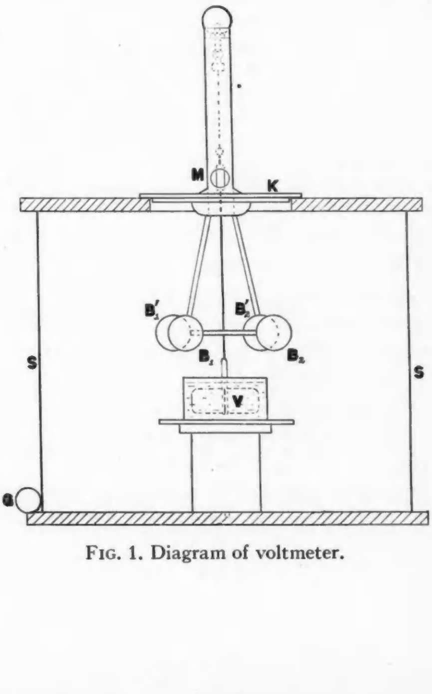


FIG. 1. Diagram of voltmeter.

[1] In private correspondence with S. R. Williams.
[2] Webster, Phys. Rev. **7**, 599 (1916); Clark, Rev. Sci. Inst. **1**, 615 (1930); Wulf, Phys. Zeits. **31**, 315, 1030 (1930).

the upper end of the steel suspension wire, there is a clamp, actuated by a screw, so that the movable balls can be raised or lowered to bring the plane in which they swing into coincidence with the horizontal plane passing through the centers of the fixed balls. The effective length of the supporting steel wire is 11.5 cm, with a moment of torsion of about 10×10^4 dyne·cm. The tube which carries the suspension wire has a window cut in one side at the level of the mirror. A hollow brass sphere surmounts the tube to avoid sharp points. A similar hollow ball at G serves as a point of attachment for the ground wire.

The potential difference to be measured is applied between the shield S and the system of balls. All four balls are charged to the same potential and the resultant, repelling forces produce a torque which turns the movable balls away from the fixed ones. Against this force of repulsion is balanced the restraining torque of the suspension wire.

Since this form of voltmeter may be used for both alternating and continuous potential differences, the calibration of the instrument was carried out by various transformers whose ratios between the primary and secondary were known. These were also checked against potentials measured with a spark gap. For potentials as high as 80,000 volts, the instrument was found to be very steady, but beyond this the leakage began to be very noticeable and the deflections became unstable.

Grateful acknowledgment is hereby made for the helpful suggestions offered by the members of the laboratory staff.

A Convenient and Effective Method of Charging Electroscopes

J. A. CULLER, *Emeritus Professor of Physics, Miami University, Oxford, Ohio*

ANY one who has worked with static electric charges and leaf electroscopes knows of the difficulties and disappointments often encountered when trying for effects that do not show up or that are weak and difficult to repeat, especially when the air is at all humid. It is highly desirable to have a method of charging which is dependable and by which the charge given may be made either positive or negative simply by throwing a switch and pressing a push button.

The device for this purpose shown in Fig. 1 has for its essential part a Model-T Ford coil. The coil is enclosed in wood, is provided with a vibrator, has three outlets to which wires may be soldered, and may be purchased at any Ford service station for about $2.00. It is effectively operated by 6 dry cells in series or by any other source of direct current of about 9–10 volts. For convenience and speed of operation a reversing switch and a push button are inserted in the battery circuit. When the lever of the switch is thrown up as shown in Fig. 1, the charge delivered to the electroscope will always be negative; if thrown down it will be positive. If the discharge point, D, is placed about 1 cm from the knob of the electroscope, a momentary pressure on the push button will cause the gold leaf to stand out at right angles. The same method may be used for charging any insulated body, such as a metal sphere supported on a glass or sulphur stand. An electroscope may then be charged again and again simply by touching it to the sphere.

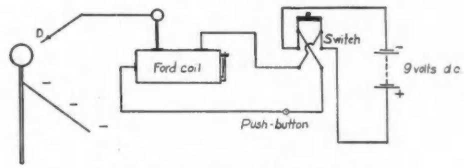


FIG. 1. Diagram of charging device.

Besides its ease and rapidity of operation and the fact that the charge may be made positive or negative simply by throwing a switch, the device has the important advantage that the charge will be delivered no matter what the humidity of the air may be.

DISCUSSION AND CORRESPONDENCE

Correspondence Between Professor A. L. Hughes and Professor John T. Tate Relating to the Program of the Tests Committee

These letters, published here with the consent of their authors, raise questions that merit the attention of every physicist who is interested in the development and welfare of higher education. Readers who are in a position to contribute to the better recognition and clarification of the issues involved are invited to address brief communications on the subject to this department of the journal.—The Editor.

Dear Professor Tate:

I was very glad to take part in the tests organized by Professor Lapp in January and June, 1933. I think that the tests were well thought out and gave us an excellent way of comparing the performances of our students with those in other institutions. This kind of objective comparison should go far towards providing each physics department with a really worth-while yardstick by which the department may feel impelled to improve its teaching, or pat itself on the back, as the case may be.

When I found that the Association of Physics Teachers planned to make the test nation wide in 1934, I was very willing to cooperate once more. I have some misgivings, however, about the present plan and if I could make an extensive poll, I have no doubt but that I should find many to share my feelings. The ground for such an attitude is at present so vague that no objection is likely to be voiced collectively. Nevertheless, I should like to know how you as a member of the Committee on Tests feel about it.

Briefly, my objection is this. So long as the test was conducted entirely by physicists, I had nothing but praise for it. Now that I find that the new series is sponsored by a group of educationists, or by a board representing their interests on the college and university level, I feel considerably less enthusiastic about the whole thing. I know that it will be pointed out at once that the five members of the committee are physicists first and last, but what I dislike is the mere fact that, in the background, we now appear to have a group of educationists. True, they may be perfectly passive at present, but I cannot imagine that they are content to remain passive; what I fear, and this fear is no doubt shared by many who have not expressed it, is that this is an entering wedge looking ultimately towards a sort of control, on the college level, of the methods of teaching and examination in physics and other subjects. I feel that physicists are fully competent to take and hold complete control over their teaching and testing. It may be argued that the educationist knows all about interpreting examination data; but, after all, this interpretation is only a matter of statistics, and surely a physicist does not need help in handling statistics!

I cannot help but feel somewhat uneasy about the situation especially if the tests continue to be sponsored by a group that is interested in introducing "education" into the training of graduate students. There is a persistent movement on foot (see any issue of the *Bulletin of the American Association of University Professors*, or some of the records of meetings of deans of graduate schools published in the *Proceedings of the Association of American Universities*) to make courses in education a part of the Ph.D curriculum. Although I have not met anybody outside departments of education in favor of it, there is nevertheless a steady urge towards this goal. Consequently, I feel that the backing of this new series of tests by the Council of Education may in part be another phase of a policy looking towards ultimate control of the methods of instruction and examination in universities and colleges by educationists. I, for one, do not welcome any step which may tend to regiment the universities and colleges in the way the high schools have been standardized.

A. L. Hughes
Department of Physics
Washington University

Dear Professor Hughes:

I share with you the feeling that physicists should have no part in furthering any attempts to regiment university or college training and that the regimentation to which the high schools have been subjected is most unfortunate. But on the other hand I am equally convinced that the present activities of the A. A. P. T. Committee on Tests, the Committee on Educational Testing, and the Cooperative Test Service are in no wise contributing to such stereotyping. Conversely, I believe the influence of these groups is vigorously opposed to any such mass control. To make my point clear it will be necessary to review briefly the history of the organizations involved in the present nation-wide physics testing program.

The American Council on Education is literally an organization of educational organizations. Most universities, colleges, and learned and executive societies are members. Its director is C. R. Mann (formerly a professor of physics at the University of Chicago). Practically none of the people backing the testing program in physics or in other subjects are educationists. The whole movement represents an effort to get test-making on a sounder departmental basis and is stimulated by a recognition of the inadequacy of the older tests prepared by educationists. Its ultimate purpose is basically antagonistic to uniformity, since it is aimed at enabling each school and each individual

instructor to deal with local problems and individual students free from the regulations which now too often constrict such efforts.

Strictly speaking, the Cooperative Test Service was formed as a coordinating agency through which specialists might collaborate to construct valid and reliable testing instruments in the subject matter fields of high school and college; the various academic disciplines were to furnish experts on content, and the statistical and measurement fields were to supply experts from their special provinces. Money was made available for this purpose to the extent of half a million dollars; and the only restrictions placed upon its use was that comparable tests in the various subject matter fields were to be issued once each year for a period of ten years and that these tests were to be offered for general use at the lowest possible cost.

The Committee on Educational Testing, the second of the Council subsidiaries, was founded for the express purpose of advising interested groups on the use of tests for the guidance of individual students. I quote from the 1933 report of this committee: "Now we are faced with the truth that the field of scholarship or culture is different for each individual because of his inherited traits, his background of experience, and his need of training for his special place in a complex society. The colleges can no longer maintain a standardized curriculum for all. They must make a curriculum for each individual."

The American Association of Physics Teachers was organized about three years ago in order to bring the attention of physicists more sharply upon problems connected with the teaching of the subject. In addition to holding annual meetings and publishing a journal, the Association has undertaken, through committees, to study some of the major problems met by college teachers of physics. It was inevitable that one committee should be organized to consider the advisability of using various forms of tests for the improvement of teaching and to work toward the perfection of tests that would be acceptable and useful. That this committee should welcome cooperation with other groups expert in this field was natural.

Through the interplay of functions and of specialized knowledge our committee, the Cooperative Test Service, and the Committee on Educational Testing are attempting to disclose and to study individual differences among physics students; and the intelligent recognition of these differences should militate against such prescriptive demands as have been written into many legal, educational requirements. The attempt to measure growth and retention differentially is directed essentially to this end.

Whether such measurement can be made valid is a question not altogether settled. Neither our committee, nor the Cooperative Test Service, nor the Committee on Educational Testing has any illusory conceptions on this point; that is why the three groups are combining their resources in order to make an experimental attack on the problem. But if we can get the problem anywhere near a resolution, one can readily see what the educational implications might be, not only for physics but for other subject matter fields as well. Suppose we really can measure growth in the academic disciplines, and suppose we have graphical indications of this growth on all school children, beginning with the first grade. Obviously we can direct these children into the lines of work consonant with their demonstrated achievement and their interests. The whole concept is perhaps Utopian but none the less seductive. Even for a mild beginning it requires the combined efforts of specialists in subject matter fields, in the educational measurement fields, and in fields of administration.

For an adequate study of student growth and retention in physics, not only is there need for thoughtful, experimental cooperation between teachers of physics and the test-making and administrative groups, but there is also need for many teachers to revaluate their conceptions regarding their functions as instructors. For example, many teachers doubtless will regard the performance of their students on the tests as indicative of something more than the students' ability or achievement. They will regard it as a measure of their abilities as teachers because they are indoctrinated with the idea that students know nothing at all about given items before they are taught but have virtually perfect knowledge of them after having been taught.

As soon as teachers convince themselves of the facts of biological heredity and will regard the individual as having definite intellectual as well as physical limitations, and, as soon as teachers conceive their functions as essentially that of discovering and understanding the possibilities as well as the limitations of students and of supplying the proper environment in which the individual student can grow—then, teachers will evaluate themselves not in terms of the average performance of their students but in terms of their ability to discover and place the individual student adequately.

Now this whole procedure calls almost for a revolution in educational thinking; and such a revolution will take time. If you have any suggestions in regard to how we can better proceed, or if you have any criticisms of these concepts, I shall welcome them most gladly.

John T. Tate
Member of the Committee on Tests and Measurements of the American Association of Physics Teachers

ABSTRACTS

Abstractors for This Number: R. J. Havighurst, Duane Roller, G. A. Van Lear, Jr.

General Physics and Related Fields

18. Hospital lighting. F. C. Raphael; *Il. Eng.* **26**, 118–128, May, 1933. The author, who is consulting electrical engineer at St. Bartholomew's Hospital, describes the types of lighting arrangements found most satisfactory for hospital wards and operating theaters. One of the most satisfactory types of lamps for the operating table consists of a large cupola, up to 1 m in diameter, which contains ordinary glass mirrors built up on a truncated cone to reflect the light from a centrally placed 100-watt lamp and lens. Green towels to surround the patient have been substituted for white towels to reduce reflection. Instead of crowding round the operating table, the students sit in an adjacent room and view on a screen 1 m in diameter a magnified image of the activities on the operating table. This is accomplished by means of a simple camera arrangement, in which the objective lens is vertically above the patient. D. R.

19. Surface tension. W. C. Hawthorne; *Sci. Mo.* **37**, 149–163, Aug., 1933. The facts and simple qualitative theory of well-known surface phenomena are presented in an entertaining and non-technical manner. The treatment is more extensive than that usually found in elementary textbooks, and would make good collateral reading. G. A. V.

20. Heavy-weight hydrogen. Harold C. Urey; *Sci. Mo.* **37**, 164–166, Aug., 1933. In this Science Service Radio Talk, one of the discoverers of the heavy isotope of hydrogen relates something of (1) the historical story of atoms as it bears on the story of hydrogen two, (2) its discovery, (3) its place in the system of elements, and (4) its properties. G. A. V.

21. The work of the Bureau of Standards in light and heat. Clarence A. Skinner; *Sci. Mo.* **37**, 273–279, Sept., 1933. The activities of the Bureau in the fields of light and heat are cataloged briefly. "A contribution to the classical problem of determining the mechanical equivalent of heat consists in pointing out that its importance is entirely artificial. . . the problem of determining the specific heat of water does not differ essentially from the problem of determining the specific heats of other substances." Four photographic illustrations are included. G. A. V.

22. The attack on the atom. John Zeleny; *Sci. Mo.* **37**, 338–343, Oct., 1933. "What is the structure of atoms? What is the nature and the arrangement of the parts of which atoms are built? What is the character of the forces that hold these parts together? How much energy do atoms possess and where is this energy located?" In answering these questions, the author traces the growth of our knowledge of the atom from Prout's hypothesis, through the development of the Rutherford-Bohr nuclear atom, down to today's powerful attacks with artificial streams of high-energy particles. The recently-discovered neutron and positron are discussed, and it is remarked that we may hope to separate out of the nuclei of some of the elements, particles with half the mass of the alpha-particle, corresponding to the nuclei of heavy hydrogen atoms. "Rutherford has expressed the opinion that we may find a neutral particle of twice the mass of the neutron." G. A. V.

23. Between the stars. Otto Struve; *Sci. Mo.* **37**, 368–370, Oct., 1933. The background illumination from the night sky is easily appreciable, even to the unaided eye, for "trees and other objects are clearly outlined as black shadows on the grayish background of the sky." Its actual intensity is about one forty-millionth of that of the day sky, and this phenomenon imposes a limitation on the range of astronomical telescopes. Observations to determine the color of the night sky are now in prospect, and their results should throw light on the cause of the interfering illumination; in the meantime, the hypothesis of interstellar dust is the most probable one. This paper is the text of a Science Service Radio Talk. G. A. V.

24. The hydrogen isotope of mass 2. F. W. Aston; *Sci. Prog.* **28**, 203–205, Oct., 1933. In this brief summary article, the author first points out that mass-spectrograph measurements of the packing fraction of normal hydrogen made in 1927 showed that its atom has a mass numerically equal to its chemical atomic weight. After the discovery of the heavy oxygen isotopes, Birge and Menzel pointed out that to bring these results into accord, hydrogen also must contain heavy isotopes. In 1932, Urey, Brickwedde and Murphy detected the presence of an isotope of mass 2 spectroscopically in the residues obtained by continuous fractionation of liquid hydrogen. The ratio between the masses of the two types of hydrogen is unique among isotopes, and quantum mechanics suggests comparatively easy separation by simple electrolysis. Lewis has obtained by this method a fraction of a cubic centimeter of heavy water, H^2H^2O, calculated to contain less than 0.01 percent of normal hydrogen. He reports that this fluid, which is indistinguishable in appearance from ordinary water, has a density of 1.1056 at 25°C, boils at 101.42°, freezes at 3.8° and has a maximum density at 11.6°C. Its heat of vaporiza-

tion is 259 cal. mole^{-1} greater than that of ordinary water. The abundance of H^2 in ordinary hydrogen was first thought to be about 1 in 4000 but this has been rendered uncertain by later experiments. It has been shown beyond doubt that an isotope of mass 3 does not exist even to the extent of one part in several millions. "The use of the new isotope in controllable quantities will be of the utmost value in establishing the positions of the lighter atoms on the physical scale of mass." ". . . its potentialities in chemistry, particularly in organic chemistry, really merit the word sensational. The possibilities of five different methanes and innumerable variations of more complex molecules are obvious, to say nothing of new modes of attack on such problems as optical activity. Furthermore substitution of H^2 for H^1 possible in the molecule is equally so in the living cell and its extension through bacteria and tadpoles to man may be safely left to the imagination of the reader. We have before us a new chemistry and a new biology." The author also discusses the work of Bainbridge, Livingstone, Lawrence and others. D. R.

Physics Teaching and Science Education

25. Characteristics of the ideal numerical problem. Alex. C. Burr; *J. Chem. Ed.* **10**, 490–491, Aug., 1933. The numerical problem should be an integral part of the structure of a course. Each problem should have definite functions to perform and should add its own increment to the educational process. Among the desirable characteristics of the ideal problem are: (1) it should be so framed that the student must contribute both thought and information in proceeding to its solution, rather than entailing only substitutions in formulas, or recasting into set forms; (2) it should be stated clearly, concisely and accurately; (3) the number of significant figures used in the data of the problem should be determined by the precision of the measurements involved; (4) it should not involve more than one new major idea; (5) each new idea should be presented in more than one problem, for the first presentation frequently results in a poor performance on the part of the student whereas a second one will not only result in emphasis but will allow the student to redeem and perfect himself; (6) the individual problems making up a given set should be of approximately the same degree of difficulty and should present the new fundamental principle involved in various guises and in different combinations. D. R.

26. Analogies in teaching freshman chemistry. John R. Lewis; *J. Chem. Ed.* **10**, 627–630, Oct., 1933. This paper points out the place of analogies in teaching freshman chemistry. A number of analogies, used in the class-room and in textbooks, are given as illustrations. The objections to the use of analogies and the advantages which are derived from their use are discussed. The conclusion is that analogies should be used because: (1) many students, in freshman classes, are not properly prepared for the conventional presentation of the subject matter; and (2) since chemistry is a growing science, it is advisable to use analogies until the more rigorous mathematical presentation can be absorbed by students. (The author.) D. R.

27. Survey course of the physical sciences for college freshmen. Will V. Norris; *J. Chem. Ed.* **10**, 631–634, Oct., 1933. The fact that a majority of the students entering the university have their major interest outside of the field of physical sciences, led the University of Oregon to organize a survey course of astronomy, chemistry, geology and physics into an integrated unit. The students through this course study the scientific method of approach and acquire a brief acquaintanceship with science without the necessity of devoting a full year to each of these fields. In this article the procedure used and the material covered are outlined. The emphasis is placed on the scientific method and not on details of subject matter. (The author.) D. R.

28. The cultural value of science in adult education. Anon.; *J. Ed.* (London) **65**, 759–760, Dec., 1933. This is an account of a symposium held at the Leicester meeting of the British Association. Speakers representing various sciences made the following points: to have cultural value science must be taught as an intimate part of ordinary human life; the action and reaction between scientific knowledge and social life must be stressed; the aesthetic elements in science should be cultivated and emphasized; the historical development of science may well be treated; science teachers should remember that "however good the matter that leaves the lecturer's mouth," what really counts is "what gets into the hearer's head"; those in training for teaching should be trained to explain things to "a railway guard, or a solicitor, or a lady teacher of music"; science teaching should help to make it clear that there are different canons of evidence available in different fields of thought; science teaching should emphasize the fact that there is a disciplined approach to every subject. R. J. H.

29. A new interpretation of the functions of high school science. Elliot R. Downing; *J. Higher Ed.* **4**, 365–367, Oct., 1933. A recent study has shown that it takes high school students two or three weeks to understand and gain facility in the application of one of the usual laws or principles of physics; and analyses of a dozen modern textbooks of physics show that the authors attempt to present from 23 to 43 principles together with a great deal of factual material not connected with these principles. The author believes that high school teachers should concentrate on helping students to master a relatively small number of physical principles which are most often needed in the solution of the problems that arise in everyday life, and that the colleges should change their entrance requirements so as to encourage such changes in high school physics. At present college entrance examinations contain much more factual material than the student can memorize if he is at the same time mastering physical principles. R. J. H.